AFIT/GSO/ENY/99M-03

SPACE LAUNCH OPERATIONS AND THE LEAN AEROSPACE INITIATIVE

THESIS

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Troy L. Endicott

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List of Acronyms

AFIT	Air Force Institute of Technology
AFMC	Air Force Materiel Command
AFRL	Air Force Research Laboratories
AFSAB	Air Force Scientific Advisory Board
AFSPC	Air Force Space Command
AIAA	American Institute of Aeronautics and Astronautics
ASC	Aeronautical Systems Center, AFMC
ATP	Authority To Proceed
BPF	Booster Processing Facility
CCAS	Cape Canaveral Air Station
CDRL	Contract Data Requirements List
CFI	Call for Improvements
CRD	Command Receiver Destruct (System)
DARPA	Defense Advanced Research Projects Agency
DDR	Downselect Design Review
DLA	Defense Logistics Agency
DMCO	Delta Mission Checkout (Center)
DUSD/A&T	Deputy Under Secretary of Defense for Acquisition and Technology
EELV	Evolved Expendable Launch Vehicle
ELV	Expendable Launch Vehicle
ETR	Eastern Test Range (Air Force)
FRR	Flight Readiness Review
GEM	Graphite Epoxy Motor (Delta II Solid Rocket Motor)
GEO	Geosynchronous Orbit
GPS	Global Positioning System

GSE	Ground Support Equipment
GTO	Geosynchronous Transfer Orbit
HPF	Hazardous Processing Facility
HPTF	High Pressure Test Facility
ICBM	Intercontinental Ballistic Missile
ICD	Interface Control Document
ILS	International Launch Services
IMVP	International Motor Vehicle Program
IPPD	Integrated Product and Process Development
IPT	Integrated Product Team
IRBM	Intermediate Range Ballistic Missile
IRD	Interface Requirements Document
ITIP	Improved Titan Injector Performance (Engine)
JPATS	Joint Primary Aircraft Training System
JSF	Joint Strike Fighter
LAI	Lean Aerospace Initiative
LCC	Launch Control Center
LCCV	Low Cost Concept Validation
LEM	Lean Enterprise Model
LEO	Low Earth Orbit
LF	Launch Facility
LPD	Launch Preparation Document
LV	Launch Vehicle
MAP	Mission Area Plan
MIT	Massachusetts Institute of Technology
MOTR	Multiple Object Tracking Radar
MTBF	Mean Time Between Failures
NASA	National Aeronautics and Space Administration
NPF	NAVSTAR Processing Facility

NRO	National Reconnaissance Office
O&M	Operations and Maintenance
ORD	Operational Requirements Document
PAF	Payload Attach Fitting
PCM	Pulse Code Modulation (System)
PDR	Preliminary Design Review
PL	Payload
PLF	Payload Fairing
PPF	Payload Processing Facility
RACS	Redundant Attitude Control System
RFP	Request for Proposal
RIFCA	Redundant Inertial Flight Control Assembly
RSA	Range Standardization and Automation Program
SC	Spacecraft
SLC	Space Launch Complex
SMC	Space and Missiles Systems Center, AFMC
SPA	Spacecraft Processing Area
SPO	System Program Office
SRB (SRM)	Solid Rocket Booster/Motor
SRR	Systems Requirements Review
STS	Space Transportation System (Space Shuttle)
TC&C	Telemetry Command and Control
TCDR	Tailored Critical Design Review
TO	Technical Order
USA	United Space Alliance
USAF	United States Air Force
VAFB	Vandenberg Air Force Base
WPAFB	Wright-Patterson Air Force Base
WTR	Western Test Range (Air Force)

Abstract

The lean concepts of *right thing, right place, and at the right time* can be applied to current and future launch systems. While much has been written on the concept of lean manufacturing and production, this thesis is the first in a series of studies from the Air Force Institute of Technology and Massachusetts Institute of Technology to investigate lean space launch operations. Nevertheless, many of the principles of lean thinking that have been applied to manufacturing and production are relevant to space operation enterprises including launch operations. The Lean Aerospace Initiative (LAI) and the concepts of lean thinking are discussed in this thesis. A review of launch system requirements and opportunities for lean practices is also presented. This is followed by an analysis of current expendable launch procedures to identify truly lean, value-added steps in launch operations. The thesis also presents a case study highlighting current Delta II expendable launch processing operations. Results of the study show how lean principles have helped the Delta launch team drastically reduce on-pad time, restructure its testing philosophy, and streamline overall operations flow. Many of these practices can be applied to other expendable launch operations and provide a strong systems baseline for the next generation of vehicles such as the Evolved Expendable Launch Vehicle (EELV).

SPACE LAUNCH OPERATIONS

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1 Introduction

For over thirty years the United States has led the world in space use and space exploration. Expendable launch vehicles have opened up space access and are deploying systems that change the way mankind communicates, lives, and functions. Military and commercial opportunities in space are limitless, but currently come at a very high price and with low mission flexibility. For the United States to compete strongly in a global commercial market and strengthen its military aerospace force, many of its launch operators are challenging existing launch processes and infrastructures. They recognize that the future of space operations depends on systems that are developed, processed, and launched through more reliable, responsive, and cost-effective means.

The lean concepts of *right thing, right place, and at the right time* can be applied to current and future launch systems. While operating in a shrinking defense budget, the U.S. Air Force still expects launch vehicles to provide assured access to space through predictable, responsive, and reliable means. In an increasingly uncertain geo-political environment the Air Force is counting on launch vehicles to provide cost-effective means of maintaining and improving space readiness, access, and mission responsiveness. The

following list highlights Air Force spacelift mission need requirements for next century's launch systems [3:4]:

a) Deploy a broad range of spacecraft to intended mission orbits.

b) Provide spacelift designs and operations processes that are supportable, maintainable, and able to meet schedule demands.

c) Successfully meet spacecraft mission assurance requirements while delivering a spacecraft payload to orbit without failure.

d) Operate at significantly lower per mission and life cycle costs than current launch systems.

e) Provide the ability to quickly respond to changing space missions and incorporate these abilities into baseline spacelift designs and concepts of operations.

Specifically, Air Force objectives for the next-generation of expendable launch vehicles include [4:23]:

- Life-cycle and annual fixed costs that are 50% less than current ELVs
- 30 to 60 day response call-ups per launch site (depending on class of launch vehicle)
- The ability to launch 26 missions per year from the United States

Efficient launch operations are imperative to achieve national spacelift goals. In order to take full advantage of new launch vehicle benefits, launch operators must assess their current operations and build efficient, lean operations that can provide savings today

and in the future with the new generation of launch vehicles. Many key players in today's launch business are members of the Lean Aerospace Initiative (LAI) consortium and are initiating steps to practice system-level approaches leading to leaner launch vehicle manufacturing and operations. As a result, launch providers offer more competitive launch services to government and commercial customers. Appendix A lists LAI consortium members as of January 1999.

1.1 Purpose of Thesis

Unlike much of the current "lean" research concentrating on manufacturing and production techniques, this thesis is a first in a series of studies from the Air Force Institute of Technology (AFIT) and the Massachusetts Institute of Technology (MIT) to focus on lean space operations. The concepts, case studies, and results of this thesis will ultimately aid in the population of the Lean Enterprise Model (LEM) maintained at MIT. This research can be integrated into tools and practices that help space launch organizations become leaner.

The primary goal of this research is to identify truly lean, value-added steps in current launch operations. This is accomplished by first introducing the reader to the Lean Aerospace Initiative, the underlying program designed to improve manufacturing and operations processes. Current launch operation requirements and mission needs are outlined in Chapter 2. Chapter 3 breaks down the launch process into its enterprise activities. A launch operations case study and analyses conclude Chapter 3, while Chapter 4 outlines future launch programs.

2 Literature Review

While much has been written on the concept of lean manufacturing and production, this study is the first within the Lean Aerospace Initiative to investigate space launch operations. However, many of the principles of lean thinking used in manufacturing and production can be applied to launch operations. The concepts of lean thinking and the Lean Aerospace Initiative are reviewed in the following sections and are followed by published launch system requirements.

2.1 The Concept of the Lean Enterprise

Creating a lean enterprise means removing all wasteful activities, unnecessary time, and error sources from a process. While such a "process utopia" may prove unrealistic, it should nevertheless be an organization's clearly defined goal. In fact, achieving perfection is the ultimate goal in any lean process. Figure 1 depicts the basic principles of lean thinking and portrays how customer value, the value stream, and perfection are related.

2.1.1 Value

Value can only be defined by the ultimate customer and is created by the system producer. Defining value makes for some interesting debates among systems engineers, but it is an important concept in any producer-customer relationship. Since the customer defines value, it is the customer's value system that should drive the problem solving process.

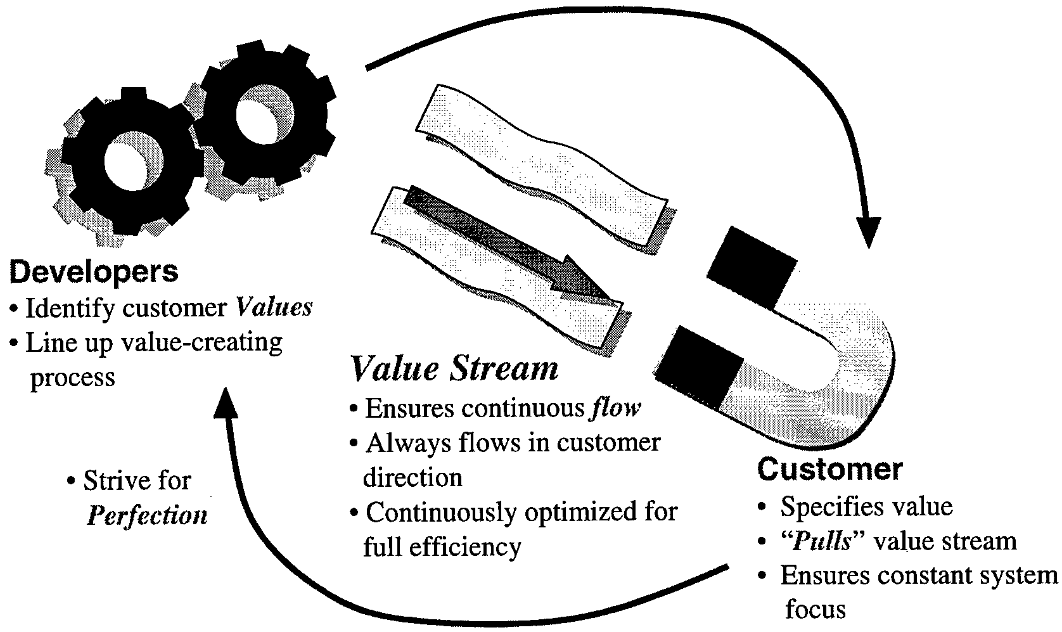


Figure 1 Elements of Lean Thinking

In his book, Patterns of Problem Solving [37], Moshe Rubinstein states a value system constitutes a framework that influences reality. He contends that a value system is "based on an appreciation of what is worth striving for and the choice of actions to bridge the gap between what is a perceived present state and the desired or preferred goal state" [37:474]. In today's marketplace, it is the customer's *product* value system that not only defines what is worth striving for, but what is ultimately worth paying for.

There has traditionally existed a dichotomy of value definition between producers and customers. The concept of value is rather subjective and may be akin to beauty as it is also determined by the "eyes of the beholder." For example, highly skilled experts may feel that they are adding value to a product by adding more high-tech features when

the customer may be looking for a system that does its job in the simplest way. Even the concept of simplicity is dependent on the person operating the system. Nevertheless, the concepts of lean thinking force the producer to focus on the ultimate customer's value when optimizing enterprise flow.

2.1.2 The Value Stream

Womack and Jones [48:19] define the value stream as "the set of all the specific actions required to bring a specific product (whether a good, a service, or increasingly, a combination of the two) through three critical management tasks of any business: the problem-solving task, the information management task, and the physical transformation task."

When the customer's value is defined, a value stream can be identified. Only upon identifying a value stream can non-value added and wasteful steps in the process be isolated and removed. The remaining activities in the lean system, or enterprise, should then be made to "flow" in the customer direction. The principles of flow management are to concentrate on managing the value stream for a specific service or product, eliminate wasteful organizational barriers by creating a lean enterprise, and continuously apply value-added techniques so that value can flow continuously [48:52–66]. If the value stream is properly focused on the customer's values and needs, the customer will "pull" the product from the producer as needed. Otherwise, the producer ends up pushing products, often unwanted, onto the customer.

2.1.3 Perfection

Process perfection begins to occur when systems are designed around customer values. *Perfect* processes encompass value streams that flow continuously and let the customers pull value from the enterprise [48:25]. Getting value to flow more directly to the customer exposes hidden flaws in the system. The harder the customer pulls, the more the impediments to flow are revealed and can be removed. Eventually, a better system will evolve through the continual application of lean principles.

Increased demand for space launch services are exposing impediments in the flow of launch operations. These demands and new requirements challenge the existing launch infrastructure and systems. As mentioned previously, today's launch customer places a high value on cost effectiveness and responsiveness. Whether launch customers know it or not, they are looking for an improved launch value stream that is leaner than today's current launch practices.

2.2 The Lean Aerospace Initiative

The Lean Aerospace Initiative originates from the International Motor Vehicle Program (IMVP). The IMVP was conducted by a team from the Massachusetts Institute of Technology as described in The Machine that Changed the World [47]. This groundbreaking study helped coin the phrase "lean production." In the five million-dollar, five-year study, the authors compared the Japanese auto industry to companies that practice traditional mass production techniques first developed by Henry Ford and specialized "craft production" companies such as Europe's Rolls Royce, Mercedes, and

Jaguar. The study highlights concepts first created by Eiji Toyoda and Taichi Ohno for the fledging Toyota Motor Company in the 1950's. The lean production techniques they pioneered a half-century ago have turned many of the Japanese auto companies into industries synonymous with quality. With the published IMVP study as a catalyst, much of the U.S. auto industry has re-engineered its fundamental management, design, and production processes. In fact, many auto manufacturers across the globe are embracing lean production as a necessity to retain a viable market share in the global marketplace. Since The Machine that Changed the World was published, many aerospace corporations have also recognized the necessity for lean production in today's competitive, but shrinking, defense market. To lower costs, shorten cycle time, and improve quality, these companies are implementing the following lean concepts:

- Re-engineering organizations and key processes starting with Integrated Product and Process Development (IPPD).
- Focusing on step-function improvements in quality, waste minimization, and customer response times.
- Building strong supplier relationships through vertical partnering and teaming.
- Using less design time, production cycle times, inventory, management layers, and capital [30].

To implement lean practices nationally, aerospace corporations have formed the LAI consortium and partnered themselves with key research institutions such as the Massachusetts Institute of Technology and Air Force Institute of Technology. The

consortium provides aerospace corporations, education institutions, and DoD partners a collaborative environment to exchange knowledge and define areas of enabling lean research. Appendix A lists the LAI member organizations as of October 1998. The LAI consortium's initial vision and current charter is to "significantly reduce the cost and cycle time for military aerospace systems throughout the value chain while continuing to improve product performance" [31].

When first chartered, LAI stood for the Lean Aircraft Initiative. As more space partners joined the team, LAI members quickly realized that lean principles can and should be applied to space activities. The LAI name was subsequently changed to include the space sector, and in November 1997 the Lean Aerospace Initiative integration team approved a proposal for confirmation by the commanders of the Air Force's Aeronautical Systems Center (ASC) and Space and Missile Systems Center (SMC).

2.3 The Lean Enterprise Model (LEM)

During the initial phases of the LAI program, the Lean Enterprise Model (LEM) was created to define lean principles and practices, and is available as a software database on the Internet. The LEM provides members of the LAI consortium a taxonomy defining what "lean" is and how it may be applied to future lean efforts.

The LEM is available to LAI consortium members and is designed to organize and disseminate research results to interested parties. The model is based on the principles of lean thinking and the lean enterprise. The LEM is maintained at the Massachusetts Institute of Technology and is populated by research-based benchmarking

data derived from industry surveys, case studies, and other research activities. The model is intended to help LAI members identify and assess "leanness" within their own organizations and provides leverage for organizational change [31]. The LEM incorporates the following principles:

a) Be responsive to change

b) Minimize waste

c) Do the right thing at the right place, the right time, and right quantity

d) Build effective relationships within the value stream

e) Strive for continuous improvement [24]

Defining LEM principles are broken down into the following twelve overarching practices that can be applied to all commercial or defense enterprises:

1. <u>Identify and Optimize Enterprise Flow.</u> "Optimize the flow of products and services, either affecting or within the process, from concept design through point of use."

2. <u>Assume Seamless Information Flow.</u> "Provide processes for seamless and timely transfer of and access to pertinent information."

3. <u>Optimize Capability and Utilization of People.</u> "Assure properly trained people are available when needed."

4. Make Decisions at the Lowest Possible Level. "Design the organizational structure and management systems to accelerate and enhance decision making at the point of knowledge, application, and need."

5. Implement Integrated Product and Process Development. "Create products through an integrated team effort of people and organizations which are knowledgeable of and responsible for all phases of the product's life cycle from concept definition through development, production, deployment, operations and support, and final disposal."

6. Develop Relationships Based on Mutual Trust and Commitment. "Establish stable and on-going cooperative relationships within the extended enterprise, encompassing both customers and suppliers."

7. Continuously Focus on the Customer. "Proactively understand and respond to the needs of the internal and external customers."

8. Promote Lean Leadership at all Levels. "Align and involve all stakeholders to achieve the enterprise's lean vision."

9. Maintain Challenge of Existing Processes. "Ensure a culture and systems that use quantitative measurements and analysis to continuously improve processes."

10. Nurture a Learning Environment. "Provide for the development and growth of both organizations' and individuals' support of attaining lean enterprise goals."

11. <u>Ensure Process Capability and Maturation.</u> "Establish and maintain processes capable of consistently designing and producing the key characteristics of the product or service."

12. <u>Maximize Stability in a Changing Environment.</u> "Establish strategies to maintain program stability in a changing customer driven environment." [32]

The LEM summary chart with metrics and enabling practices is found in Appendix B. Supporting practices and other data external to the model are available to LAI members and maintained in the detailed online version of the LEM. While the LEM is designed to tell users what lean is, it does not tell producers or operators how to get lean. Since leanness may be applied to different processes and measured by an assortment of metrics, it is up to user organizations to apply lean approaches in their systems engineering processes. Lean thinking forces organizations to consider not just separate activities in a process, but the total enterprise. Only after the total enterprise is identified can the inefficient or wasteful activities be improved or rooted out.

2.4 Lean Aerospace Initiative Space Research

Lean principles can be useful in any manufacturing process. While initial lean-process studies focussed on the automotive industry, lean principles have since been applied to a variety of systems where lower cost manufacturing and operations are desired. For example, NASA is an organization facing downsizing quotas. To help maintain its focus on its research and development roots, NASA has handed over its Space Shuttle launch operations to a private consortium, United Space Alliance (USA), a

joint venture of Lockheed Martin and Boeing [43]. By handing over its Shuttle launch operations, the government expects to reduce its operating costs while better utilizing downsized organizational resources. The USA contractor teams are also members of the Lean Aerospace Initiative consortium. The transition of operations to the USA has led to lean principles that are eliminating waste in the complicated Space Shuttle launch cycle. Quality assurance research conducted by Mr. Gerald VerDuft at the California State University at Dominguez Hills states that under a new USA system, workers at the lowest logical level are being empowered to certify quality of work while 700 additional launch processing tasks are being handed over from NASA to the USA staff [45:25]. Of course, the challenge and primary concern for NASA is to maintain its focus on safety and reliability while it converts to more efficient lean operations.

The NASA/USA example is an illustration of where some lean principles are being applied to the space launch arena. Many defense firms are applying lean processes across the board by improving on current manufacturing techniques and designing these changes into future manufacturing designs and prototypes.

Perhaps one of the best reported examples of the use of lean principles in aircraft design is Lockheed Martin's F-22 advanced fighter aircraft program. Lockheed's goal is to use lean concepts to optimize manufacturing flow and eventually cut the F-22 delivery times from 32 months to 24 months [25]. The team is determining long-lead production items and is finding opportunities to remove them from the critical path to ultimately optimize production flow.

Another good example of lean manufacturing is how The Boeing Company has improved the process of manufacturing bulkheads in its F/A-18 fighter aircraft. While an aircraft bulkhead may not seem like a part requiring drastic changes in production methods, production improvements in this critical part can be realized throughout the complete aircraft system. The older FA-18 C/D model's bulkheads required a 90-piece sheet metal build up, hundreds of specialized tools, and a long 29-day manufacturing cycle. The new E/F model's bulkheads are now machined as a one-piece part and require only eleven assembly tools and a fraction of the original manufacturing time. The new bulkheads are also 7.5 pounds (3.4 kg) lighter than their predecessors. Most importantly, fabrication of the new bulkheads saves time, money, and labor [15]. Boeing is fundamentally changing the way it builds military aircraft and is incorporating lean principles at the lowest common denominator.

Boeing's new lean manufacturing culture can trace many of its roots to the design of the commercial 777-jetliner aircraft. The new lean practices introduced in the 777 project have had a significant impact on the award and implementation of subsequent Boeing projects such as the Joint Strike Fighter (JSF) [5]. Table 1 lists the differences in the old and new ways Boeing is building its advanced aircraft. However, for the key practices in Table 1 to become effective over the long run, management and workers must maintain a commitment to the changing cultural environment. Employees also have to be empowered by top management to make the cultural changes and build routines that will eventually become standard practices.

Table 1 Lean Approaches in JSF Prototype Design [15]

Old Practices	*New Practices*
Engineering drawings	100% Computer-based solid modeling
Physical mock-ups of designs	Computerized "virtual" designs
Paper-based assembly instructions	Computerized assembly simulation
"Hard" assembly tooling	Laser-designated positioning
Inspections at assembly milestones	Built-in process inspection
Foreman required at production level	Assign team leader
Functional organization of workers	Empowered integrated product teams

Similar lean principles are being applied to the development of the next generation of spacelift vehicles. In addition to manufacturing research, the LAI consortium is attempting to capture lean practices in the operational space sector and has outlined preliminary areas of interest to include:

a) Optimization of space system testing

b) Launch operations

c) Use of modeling and simulation to reduce spacecraft test spans

d) Lean practices in space asset command and control, including on-orbit operations [46]

While all the proceeding topics present interesting research avenues, the thrust of this study is on launch operations.

2.5 Current Launch Practices, the Need for Lean

Even though current United States launch vehicles will be used beyond the year 2000, they are already operating at their maximum capabilities. One reason for the inherent inefficiency of today's launch systems is the heritage of their technologies. Today's launch vehicles are primarily based on Cold War Intercontinental Ballistic Missile (ICBM) technology. Even the mighty Titan IV is a derivative of a 1950's-era Titan ICBM. ICBMs were initially designed to carry small warheads into sub-orbital trajectories, and early designers probably did not anticipate their systems being used to launch sophisticated satellites into low-earth (LEO) or geosynchronous (GEO) orbits.

Basic acquisition strategy states that to minimize development costs, it is desirable to meet new missions by first modifying existing systems and then reconfiguring associated operating procedures or tactics. This concept is easily seen in the role the Air Force's B-52 bomber aircraft has played in the last half-century. The B-52 has transformed from a high-altitude, nuclear weapon platform to a low-altitude conventional weapon delivery system as seen in the latest B-52H model. While today's constant upgrades may prove a viable and cheaper solution for bombers, the same is no longer holding true for the current fleet of launch vehicles. The fact that the United States has been able to convert nuclear delivery systems into useful and rather sophisticated launch systems is a testament to progress and peace, but such progress has come with a price.

Air Force Space Command has declared that continued production, operation, and maintenance of today's launch vehicles are cost ineffective for two reasons. The first is

the escalating expenses associated with inefficient launch systems and their extensive infrastructures. The second is due to outdated launch system technologies, designs, and manufacturing techniques [4:6]. To complicate matters, national spaceport facilities, processes, procedures, and launch infrastructures are not standardized. Even though Cape Canaveral Air Station and Vandenberg Air Force base may launch similar systems (i.e., Titan IV, Atlas II and Delta II systems), launch procedures and infrastructures are different for each base. The non-standard logistics that is required for unique systems in each facility have produced one-of-a-kind range hardware. The knowledge base required for operating and maintaining each unique system is also eroding as more technicians retire or leave the ranges. To keep up with this declining knowledge base, increasingly specialized training is required to operate and maintain the variety of equipment. The Air Force also estimates that today there are more than 25,000 outdated range components with no sources of spares [21:41]. It projects that future requirements for existing launch systems combined with further equipment obsolescence and increased training requirements will drive costs beyond budgetary limitations. Table 2 is an Air Force subtask assessment of current launch services. The following sections highlight operation areas listed in the table that need increased consideration for improvement.

Table 2 Air Force Spacelift Deployment Subtask Assessment [21:42]

Capabilities / Tasks	Capable *Ability to perform required tasks*	Operable *How responsive and maintainable is the system?*	Reliable *Ability to initiate and complete tasks.*	Economical *Efficiently operate, sustain, and evolve capabilities*	Overall Rating
Generate the Launch Mission	A	L	●	L	L
Execute the Launch Mission	●	●	A	L	L
Perform Post-Launch Operations	●	L	●	L	L
Employ the Launch Ranges	A	L	●	L	L
Spacecraft Initialization	A ↓	L	A	L	L

A *Adequate Capability* L *Limited Capability* ● *Data Not Available* ↓ *Declining Capability*

2.5.1 Launch Mission Generation

Current launch systems lack standard payload interfaces. Separate payloads on the same vehicle may require different interface configurations. Individual interfaces add complexity to launch processing and require high levels of skill to craft the unique parts. With increased launch requirements and the need for reduced cycle times, such specialized production of vehicle-payload interfaces hinders the overall responsiveness of the launch fleet.

2.5.2 Launch Mission Execution

The current launch fleet has an impressive record of successfully delivering payloads to orbit. Figure 2 lists recent success records of the latest versions of U.S. expendable launch vehicles through fiscal year 1998.

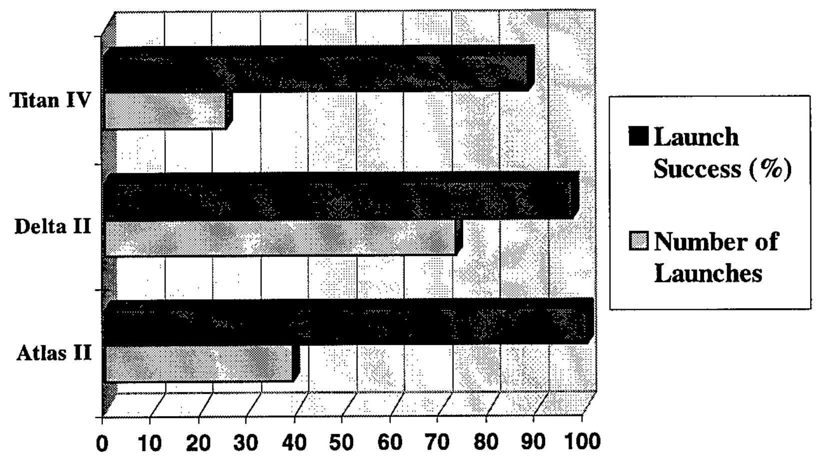


Figure 2 Launch Success Rate for Modern ELVs [1]

Even though launch providers are successfully launching payloads into orbit, the execution of the launch process remains in question. Current launch execution is labor intensive and again, nonstandard across the board for different launch vehicle systems. The labor-intensive operations and increasing tempo of launch requirements are cause for concern in a shrinking Air Force [21:40].

The choice of launch propellant is also becoming an increasingly significant issue to operators. Operations with vehicles using large amounts of solid propellant such as the Titan and Delta systems are becoming more and more restrictive due to the toxic nature of launch exhaust products. Launch ranges must run launch-day risk assessments that

model the vehicle exhaust and predict chemical concentration levels. If these levels are too high and pose a risk to the environment, wildlife, or outlying population centers, the launch will be postponed until meteorological conditions are more favorable [21:40]. Operations at Vandenberg, AFB, California are especially susceptible to environmental delays. Strict California laws require a broad array of environmental assessments, restrictions, and fees. However necessary, these additional requirements complicate the launch process, require more manpower to manage, increase launch costs, and run the risk of delays that affect launch availability and responsiveness.

2.5.3 Post-Launch Operations

Activities after a launch may have low-visibility in the scope of a launch process, but are nonetheless crucial for sustained operations. Refurbishment activities are manpower-intensive and costly. Launch pads must be inspected, repaired and refurbished to pre-launch conditions. Post launch refurbishment typically takes seven to 20 days, depending on the damage [21:41].

2.5.4 Launch Range Employment

Again, the non-standard nature of the ranges and launch systems adds complexity, costs, and large amounts of specialized equipment, training, and logistics. As a result, operations and maintenance costs for the ranges are on the order of $400M to $500M per year [21:41]. The current launch-range infrastructure also makes it impossible to support multiple operations. For example, the ranges are currently incapable of conducting two separate "wet-dress rehearsals" simultaneously. Wet-dress rehearsals are required

procedures and include pumping propulsion fluids into the launch vehicles on the pad and are sometimes followed by a full, simulated countdown.

2.5.5 Spacecraft Initialization

The ability to support future systems on existing ranges is limited. Any new launch or support system introduced requires extensive modifications to the existing range infrastructure. Currently, every new launch cycle involves significant software and often hardware modifications. This requires a high level of skilled operators and engineers to prepare the range for each launch. With each new launch procedure and set of modifications, the ranges incur high rehearsal and training costs [21:42]. With a new set of launch vehicles planned for the next decade, many of the existing launch deficiencies can be viewed as opportunities for change.

2.6 Future Launch Requirements

In the global drive to make systems "better, cheaper, and faster," lean processes must be infused into current launch operations while preparing for planned future developments. Data, from a 1997 study gathered by the Aerospace Corporation for NASA/Marshall Space Flight Center and Headquarters Air Force Space Command [2], shows that there is no better time than the present to optimize the current launch operations infrastructure, technologies, and systems. Table 3 lists anticipated U.S. spacelift requirements in the year 2000 to 2010 time frame.

Table 3 Near-Term Spacelift Requirements [2:46]

LEO Payload	Military	Civil	Commercial	Total
Small (<5000 lb_m)	1 to 2 per year	4 to 8 per year (experiments, weather)	16 to 32 per year (LEO com. sats)	21 to 42 per year
Medium	7 to 11 per year	1 to 4 per year	22 to 49 per year (LEO, GEO com sats)	30 to 64 per year
Heavy (expendable)	2 to 3 per year	1 every 4 or 5 years (Cassini type)	4 to 6 per year (GEO com. sats.)	6 to 10 per year
Heavy (Space Shuttle)	---	7 to 8 per year (Space Station missions)	---	7 to 8 per year

To put these launch requirements in an economic perspective, Figure 3 depicts the anticipated markets in the same time frame for launch services by sector.

Based on these economic forecasts, the largest space transportation market in the 2000 to 2010 time frame is in commercial medium lift operations. This sector includes the Lockheed Martin's Atlas II, Boeing's Delta II and III, the Russian Proton, and the French Ariane V class of launch systems. Flight rates are increasing in the medium-lift sector and will continue to grow as new payloads are lifted into orbit and existing constellations are replenished with new satellites. The projected 30 to 64 launches per year in the 2000 to 2010 time frame for U.S. systems is nearly double that of a 1996 capability of 27 launches [2:48].

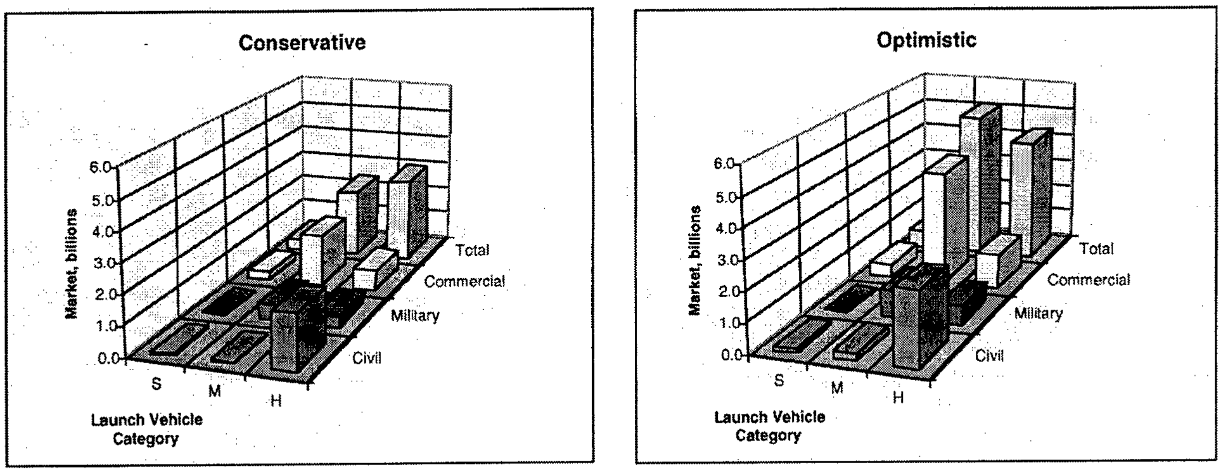


Figure 3 Future Launch Markets by Sector (Excluding Teledesic) [2:52]

Using historical flight rates of existing Atlas and Delta systems, the Aerospace study forecasts that the combined maximum rates the two systems can deliver in the near future will be approximately 29 flights per year. Including future medium-class Evolved Expendable Launch Vehicle (EELV) and Sea Launch estimates, the forecasted flight rate per year for U.S. systems is 58 launches [2:60]. To meet a medium-ELV demand of 30 to 64 launches per year, launch providers need to build operation enterprises that are better and faster than today's. Of course, any lean practices applied to today's medium lift launch operations should pay off in increased savings for future payload customers and ultimately increased revenue for the launch providers themselves.

3 Launch Operations Research and Analysis

To capture the essence of this thesis and show how lean principles can be applied to current launch operation enterprises, the following chapter focuses on the actual launch process. It begins with a generic methodology that describes the core activities in a basic launch operations enterprise. With this in mind, two medium-lift launch operations are covered. The first is a general description of the Russian Proton launch system, and the second is an in-depth case study highlighting Boeing Delta II launch operations. Both launch operation systems employ significant lean practices and can serve as models for operators searching for improvements in their launch enterprises.

3.1 The Launch Operations Enterprise

A launch vehicle undergoes a series of complex preparation activities before it ultimately sends its payload into space. Figure 4 represents the scope of the launch operations process. The outside ring depicts common activities required in the launch process. The inside ring lists the important parameters, or *enterprise level metrics*, that can be applied to launch activities. Launch metrics and applications are discussed in greater detail in the following sections.

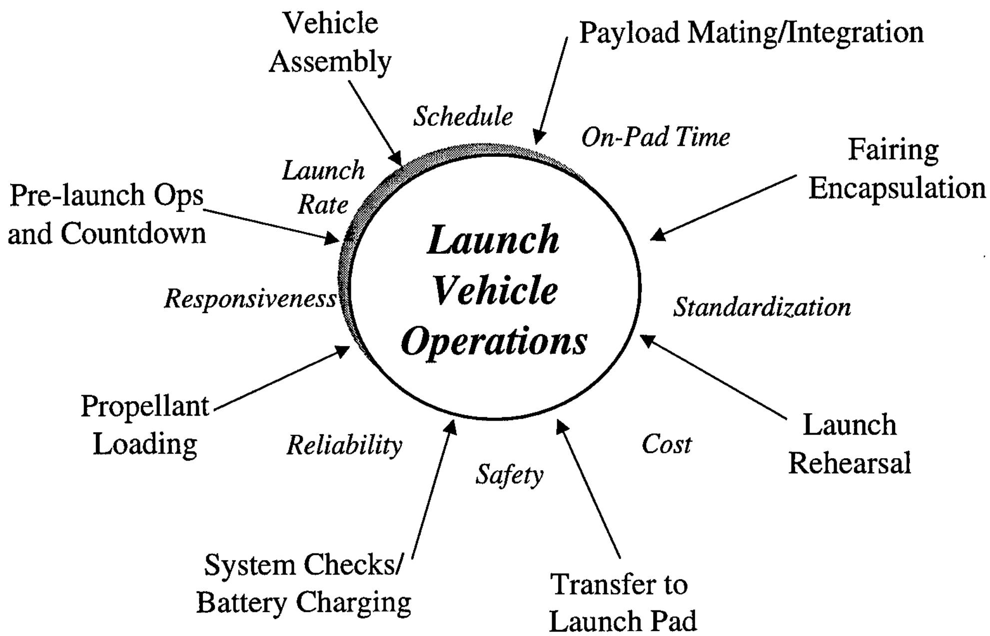


Figure 4 Launch Operations Network

3.1.1 Enterprise Metrics

A typical set of parameters, or *enterprise level metrics*, can be applied to most launch enterprises. The launch activities depicted in Figure 4 may provide a basic framework for launch operations, but the extent of their "leanness" is commonly measured by the following metrics.

3.1.1.1 Cost

Launch cost is perhaps the most important metric to launch providers and payload customers alike. Launch cost includes all costs needed to launch a payload into orbit and the costs to support the launch operations infrastructure.

Air Force Space Command led a mission area planning (MAP) team to evaluate current U.S. launch operations and listed six prioritized space launch deficiencies [44]. The primary deficiency is costly launch systems. The current cost of launch vehicles, in terms of dollars per pound of payload delivered to orbit, ranges from $5,000 to over $15,000 per pound [44:19]. Additionally, recurring costs of maintaining and sustaining existing launch range infrastructures increase overall expenditures. These high costs are forcing launch operators and providers to design leaner launch systems and supporting enterprises that meet future cost goals. As part of NASA's strategic research framework, future space access goals have been identified. These goals are to [42]:

- Reduce the payload cost to low-Earth orbit by an order of magnitude, from $10,000 to $1,000 per pound, within 10 years.

- Reduce the payload cost to low-Earth orbit by an additional order of magnitude, from $1,000 to $100 per pound, by 2020.

Similarly, Air Force objectives for the next generation of launch vehicles include life cycle and annual fixed costs that are 50% less than the current operations [4:23]. The use of lean practices in launch system design and operations can increase customer savings by eliminating non value-added activities in the launch process.

3.1.1.2 On-Pad Time

On-pad time is another metric used in the launch business and is usually calculated in days. On-pad time is a primary measurement for Air Force space launch squadrons when determining launch service provider award fees [11]. This is an example

of the customer creating and measuring value. However, reducing on-pad time should be just as important to the launch customer. Logically, every minute a payload sits on the pad is a minute wasted in space. This becomes a concern with commercial payload customers who are dependent on the immediate revenue the payload will provide once in orbit. Some customers lose millions of dollars per day in potential revenue when their payloads are confined to a launch pad [49].

It is also important to minimize on-pad time to maintain government launch responsiveness and mission flexibility. Even though commercial payloads are occupying an increasing amount of United States launch pads, those pads are still owned by the U.S. government and may be needed to support short notice space missions.

Given that on-pad time is a widely used metric and key indicator for launch provider performance, one should understand its conditional value. Launch service providers may extend the time a vehicle is on-pad if there are no imminent situations requiring the use of a launch pad or no near-term requirements on the launch manifest. While launch providers may not need the extra time to complete on-pad operations, they may take advantage of the flexibility in the launch schedule and spread work resources to other activities in the launch process. Adjusting production flow times to meet customer demand is defined as controlling activity "takt" time [48:55]. However, launch providers must first have a clear understanding of their launch enterprise activities and the times associated with each activity before takt time can be considered and launch operations synchronized with customer demand.

3.1.1.3 Launch Rate

Launch rate is measured in launches per month or year and usually controlled by the launch manifest. The manifest is the primary scheduling tool of upcoming launches used by launch providers to synchronize their operations flow. Launch rates vary according to customer requirements and tend to be higher in years with population of new satellite constellations or increased replenishment activities. Maximum launch rates are good indicators of a launch provider's efficiency of operations and its ability to respond to increased demand.

3.1.1.4 Reliability

Launch vehicle reliability is usually expressed as the probability that a launch vehicle will deliver a payload to orbit. Expendable launch systems are generally rated according to their launch successes, failures, or partial failures. Complete launch success is typically defined as a vehicle delivering its payload safely into its intended orbit. Launches are usually termed failures when a catastrophic system failure occurs, while a partial failure would be delivering a payload to an orbit other than the one intended, thus reducing its useful life.

3.1.1.5 Schedule Slips

Schedule slips can be an indicator of the level of leanness in a launch operations enterprise. While some slips are unavoidable due to weather and other uncontrollable circumstances, others may be a direct reflection of the overall operations effectiveness. If a schedule slip occurs while a vehicle is being processed on the launch pad, the delay

could have a ripple effect and ultimately affect other systems waiting for use of the pad. An Air Force Scientific Advisory Board study states that that the existing launch infrastructure is inefficient and has caused launch delays that have tripled in the last two years [12]. This study recommended modernization and streamlining of launch facilities to reduce schedule slips.

3.1.1.6 Standardization

Operation standardization helps streamline launch-processing flow. Standardization metrics are applied to the number of common systems, operating procedures, or launch processing activities across the board for a given launch system, combination of systems, or launch sites. Properly standardized launch systems and launch support operations decrease overall logistics and support costs, streamline training, and provide a common foundation for continued process maturation.

3.1.1.7 Safety

In a drive to build better, faster, and cheaper systems, safety is a metric launch providers will not compromise. Boeing is one company that regularly monitors safety incidents and actively pursues a 100% safety record across the board for its launch personnel [5]. In designing lean practices, safety should still be a primary consideration. In addition to launch vehicle processing techniques, launch safety analyses and procedures can be applied to launch hazard assessments, vehicle failure modes and effects modeling, launch trajectory simulations, and intelligent range safety systems.

3.1.1.8 Responsiveness and Availability

As previously mentioned, an Air Force Mission Area Plan (MAP) listed the primary deficiency in U.S. launch operations as costly launch vehicles. Scoring a very close second was unresponsive spacelift operations [44:19]. Launch system responsiveness is the ability to meet additional demands for rapid augmentation of on-orbit assets through increased launch rates [27]. Launch responsiveness is also commonly considered a measure of flexibility in a launch operation enterprise and includes factors such as launch availability, vehicle reliability, and a launch provider's surge-rate capacity. Joseph Loftus and Charles Teixeira from NASA Johnson Space Center [29:672] define expected launch availability as a function of vehicle reliability, production capacity, the ability of the launch operations infrastructure to support a desired launch rate, existing launch commitments, and demonstrated stand-down times following a failure. This measure of launch availability can be expressed by the following relationship:

$$A = 1-[L\,(1-R)\,T_d\,/(1-1/S)],$$

where R is the vehicle's reliability (section 3.1.1.4), L is the nominal or scheduled yearly launch rate, T_d is the demonstrated (or estimated) stand-down time after a failure (in years), and S is the surge rate capacity over and above the planned launch rate (*e.g.* S=1.25 means the system can achieve a flight rate 25% higher than the planned launch rate, L).

The MAP study states that launch availability and responsiveness of current expendable launchers have had little effect on existing launch dates since payloads are

typically not standing ready for launch. Nevertheless, if contingency operations demand a rapid augmentation of on-orbit assets, current launch systems will be unable to meet those requirements [44:19]. In building leaner launch enterprises, launch providers need to design more responsive systems in order to protect our nation's vital space interests.

3.1.2 Launch Activities and Enterprise Flow

Before activities in the launch process can be determined as value-added, a launch model must be identified to illustrate a sequence of launch activities. Figure 5 depicts the flow of typical launch activities, regardless of launch vehicle or payload. As seen in the figure, launch processing generally consists of two parallel processes for booster assembly and spacecraft/payload preparation. A tertiary set of ongoing activities throughout the processing cycle usually includes provider and customer interactions, meetings, and working groups. Common documentation products include interface requirements documents (IRDs) and interface control documents (ICDs).

Timelines vary for each launch activity in the cycle and are dependent on external, operational, and infrastructure factors. Overall process efficiency depends on the initial systems architecture put in place to support the launch mission. Early launch center architects in the 1960's most likely did not realize the impact their designs would have on launch operations so many decades into the future. For example, the culture of the former Soviet Union significantly shaped current Russian launch operations.

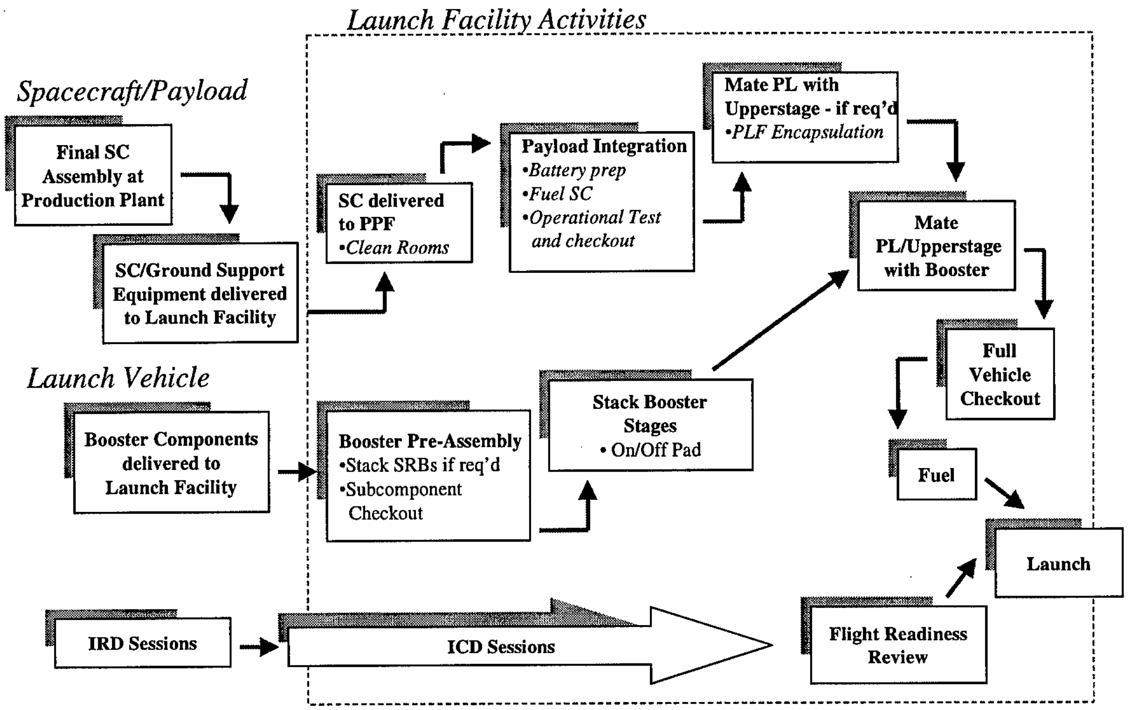


Figure 5 Launch Enterprise Flow Activities [27]

Like the United States, Russians view space access as vital to their national security. Frequent and reliable access to space was key to the former Soviet Union from the outset of the "space race." Since launching its first satellite, the Sputnik 1, the Soviet Union became dependent on its space assets to maintain global communications, monitor Russian borders, and to keep an eye on their Cold War adversary, the United States. The early Soviet satellites did not have the same mean-time-between-failures (MTBFs) and redundant systems as their American counterparts [27]. Instead of engineering satellites to stay in orbit for longer durations, the Soviets designed their launch infrastructure for constant re-supply and replenishment of their constellations. The harsh weather conditions of its launch centers also helped drive Soviet launch processing. Reducing

rocket on-pad time was a necessity to minimize weather exposure to the sensitive payloads. Therefore, it was necessary to assemble rocket bodies off-pad and the horizontal "assembly line" operations were developed as a result. Combined with the military strategy of constant satellite re-supply and the need for horizontal processing, the Soviet engineers helped develop a process that many today consider a benchmark for launch processing [27]. At their peak, the Soviet Union was launching over 100 vehicles per year, still an astounding feat for any space-capable nation [27]. The Russian launch infrastructure designed behind the Iron Curtain is now considered one of the most optimized flow operations in the space launch business. It wasn't until the end of the Cold War that the Americans could "capitalize" on the Russian launch processes.

3.2 The Proton Launch Process – A Russian Perspective

The following section briefly addresses the Russian Proton launch processing operations. While Russian systems engineers did not have the Lean Aerospace Initiative and its practices in mind when designing their launch operations flow, they built a launch concept with many practices that are considered "lean" and can serve as a model for optimizing current and future launch activities.

3.2.1 Proton History

The Russian Proton launch vehicle is considered one of the most capable expendable launchers in service today. It has been a mainstay medium-lift vehicle for Russian operations since 1970. The western world got its first glimpse of the Proton launch vehicle in 1984 when it lifted two Vega probes to Haley's comet in December of

that year [23:132]. The Proton comes in three-stage (D-1) or four stage (D-1-e) variants with the fourth stage used to insert payloads into orbit and interplanetary trajectories. The three-stage D-1 model can lift approximately 44,100 lb_m (20,003 kg) to a 185 km circular orbit and the four-stage D-1-e model can lift approximately 12,100 lb_m (5,488 kg) to a geosynchronous transfer orbit at a 28.5 deg inclination [23:133]. The lower three stages of the D-1-e are identical to those of the three-stage D-1. The configuration of the four-stage D-1-e is depicted in Figure 6.

The Proton's launch rate grew from six launches in 1970 to a peak of thirteen in 1985 [23:133]. Based on information furnished by the Aerospace Corporation, launch reliability for the Proton D-1 and D-1-3e program since 1970 is approximately 88% and includes a reliability record of approximately 92% over the last 50 launches [1]. The increase in launch reliability in recent years has made the Proton system a commercially viable option for today's global launch market. Supporting Proton launch success data is listed in Appendix C.

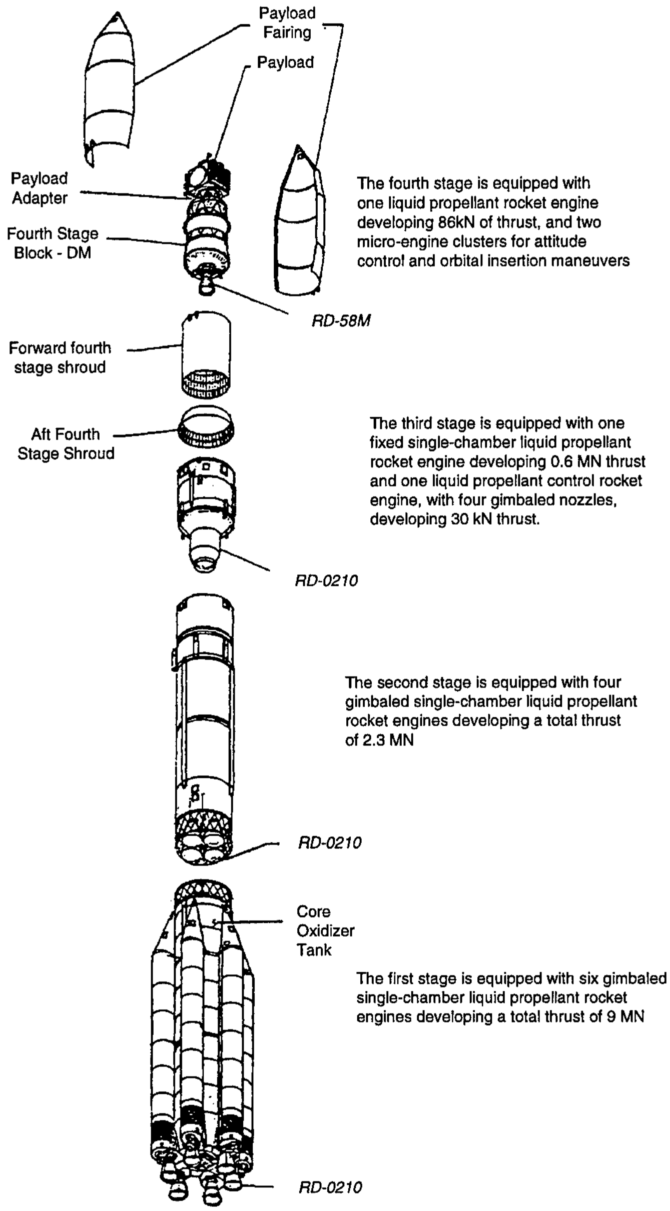


Figure 6 Proton/Block DM (D-1-e) Staging Elements [22:2-10]

3.2.2 Proton Launch Operations

All Proton launches are conducted at the Baikonur Cosmodrome near Tyuratam in the Republic of Kazakhstan. The average annual temperature is 55 deg Fahrenheit (12.8

deg Celsius), and ranges from extremes of – 40 degrees Fahrenheit (– 40 deg Celsius) in the winter to 113 degrees Fahrenheit (45 deg Celsius) in the summer [22:9-1]. Unlike United States launch sites, the Baikonur climate requires a very high level of protection from the elements for both launch vehicles and their payloads. Launch analysts consider Baikonur climate conditions as a major factor in designing the Russian launch operations flow where all assembly and integration activities of the Proton launch vehicle stages are completed indoors [27]. Assembly and integration of the launch vehicle stages are performed horizontally, off-pad, and in special climate-controlled facilities. Even the payload is mated to the fourth stage vertically off the pad and rotated to the horizontal for fairing encapsulation. The encapsulated payload and fourth stage is then loaded onto a climate-controlled railcar and shipped to a separate horizontal facility where it is mated to the launch vehicle. The complete launch system is shipped on a transporter-erector cart (Figure 7) and delivered to the pad four to five days from the launch day.

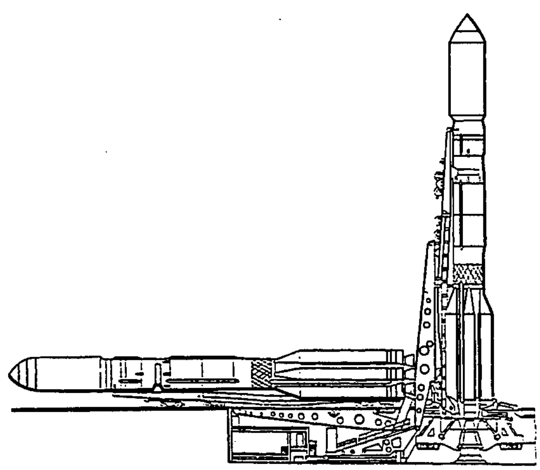


Figure 7 Proton Transporter Erector System [22:9-47]

Figure 8 depicts the generalized order of operations of the Proton launch process for western payloads launched at the Baikonur site.

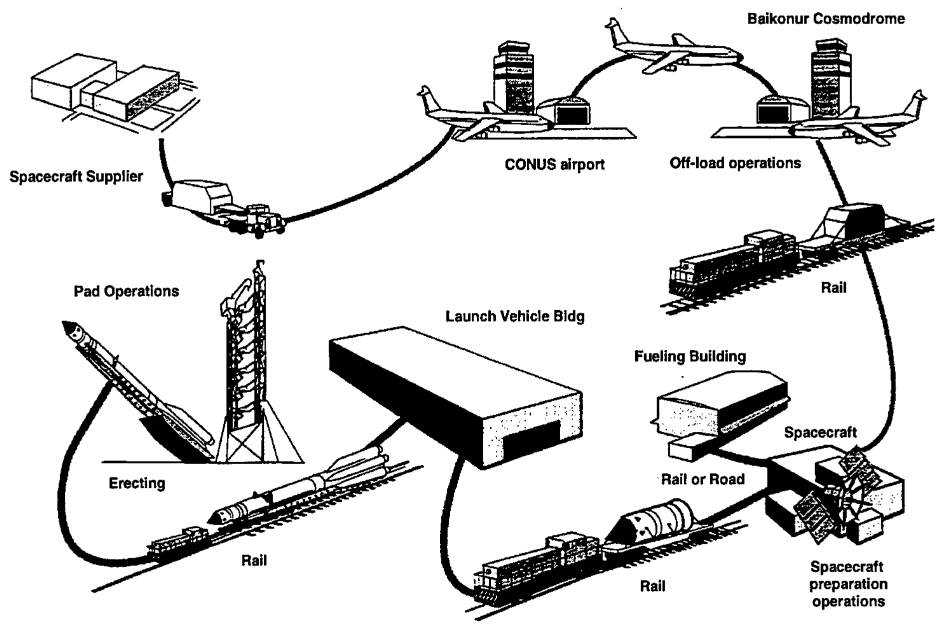


Figure 8 Proton Ground Operations Flow [22:9-16]

This "assembly-line" format of processing launch vehicles and their payloads is very different from United States methods. While current U.S. expendable vehicles tie up launch pads from 21 to over 100 days, the Russian Proton system occupies the pad for only four to five days. Since the Proton flow minimizes on-pad operations, the majority of launch vehicle components are tested and processed off the launch cycle's critical path. This adds flexibility in launch resource availability and builds in a higher level of responsiveness in the total launch operations enterprise. Figure 9 shows an overview of the Proton launch site operational flow for western customers. It is rather remarkable that customers can arrive at Baikonur and launch their satellites in little over a month.

Even more remarkable is that the Russians have sustained this same process flow time and flexible launch enterprise for nearly thirty years [27].

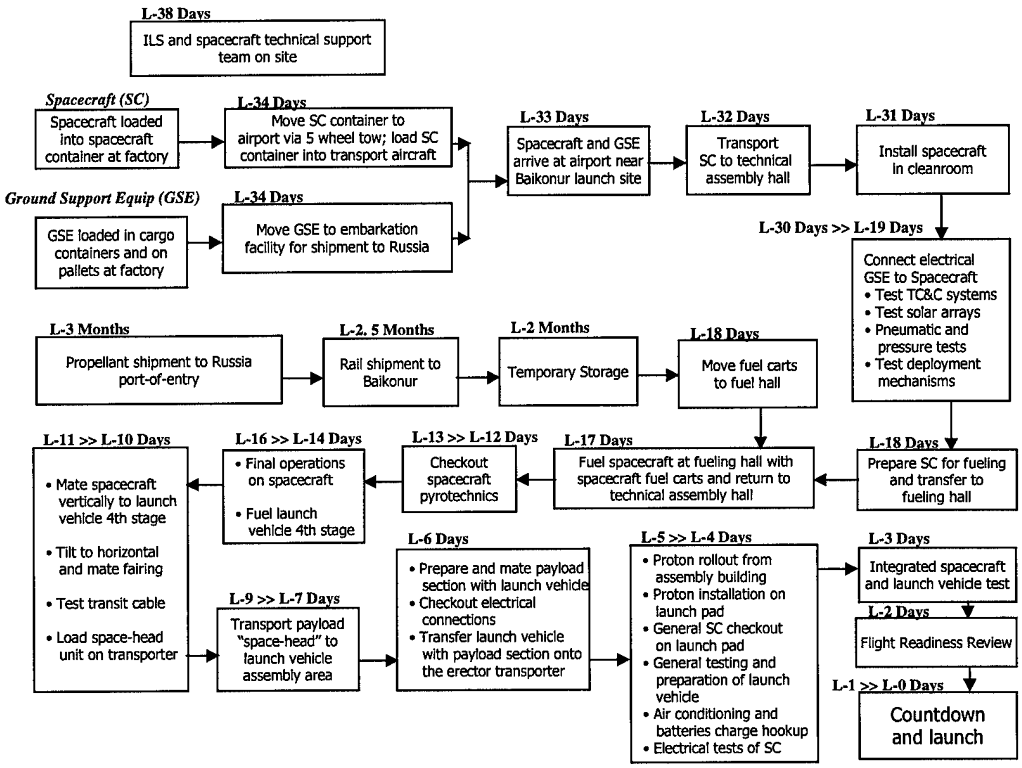


Figure 9 Russian Proton Payload Process Flow [22:2-16]

Launch providers in the United States have studied the Russian launch processing system and are applying many of those practices to current and future launch system designs. The Missiles and Space Division of Lockheed Martin has partnered with the Proton's builder and fourth-stage supplier companies, Khrunichev and Energia, to form International Launch Services (ILS) to market commercial Proton launch services [22:1-1]. EELV designs from Lockheed and Boeing utilize many of the same efficient launch processes as the Proton system (such as horizontal processing and minimized pad

operations) and will fundamentally change the United States launch business. However, U.S. expendable launch operators and contractors are not necessarily waiting for EELVs before building lean launch enterprises. The following section highlights the lean improvements Boeing has implemented in its current medium-lift expendable operations.

3.3 Boeing Delta II Case Study

Current launch processes present many opportunities for improvement. Launch operators are starting to recognize these opportunities and are working to implement lean initiatives that will pay off in higher launch rates, streamlined flow operations, and higher success rates. The launch business market itself is forcing operators to think and act lean. The Boeing Company, with its Delta II and III family of launch vehicles, is already employing lean principles in its launch processes. The following section is an introduction to the Delta II and III launch systems and is followed by a case study that highlights Boeing's lean launch practices.

3.3.1 Delta II and III

The Boeing Delta II is a medium capacity expendable launch vehicle and a derivative of the original McDonnell Douglas Aerospace's Delta vehicle launched in 1960. Including the maiden flight of the Delta III in August of 1998, there have since been 242 successful Delta launches out of 262 giving the Delta-family a success rate of 94.3% [9]. Figure 10 depicts the evolution of the Delta rocket family.

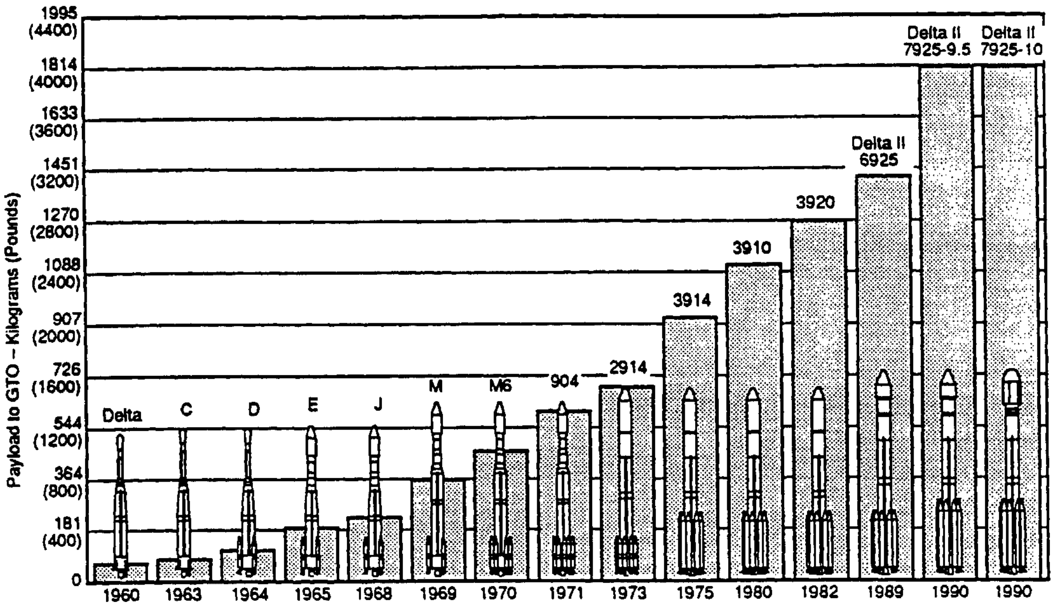


Figure 10 Delta Launch Vehicle Evolution [33:1-2]

Delta rockets come configured in two or three stages depending on mission requirements. The medium Delta II rocket is augmented by its smaller strap-on solid graphite epoxy motors (GEMs) that can be configured in clusters of three, four, or nine depending on mission requirements. With nine GEMs, the latest Delta II 7925 model can lift a substantial 4,010 lb_m (1819 kg) to geosynchronous transfer orbit (GTO).

The Delta III is Boeing's latest launch vehicle and is its first large vehicle developed wholly with private funds. The Delta III is a modified Delta II, but is most distinguishable by the widened interface on the first stage that facilitates integration of a completely new second stage. The Delta II's second and third stages are replaced by one cryogenic oxygen/hydrogen upper stage capable of 25,000 lb_f (111,205 N) thrust. Unlike the Delta II, three of the nine Delta III's Alliant Techsystems GEMs are fitted with a thrust vector control system to enhance vehicle maneuverability and control. Delta III

produces 1,099,540 lb_f (4,891,000 N) of thrust from the core engine and six solid rocket strap-on motors and can carry 8,500 lb_m (3,855 kg) of payload into geosynchronous transfer orbit [13].

Boeing launches the Delta systems from two government-owned launch pads at Space Launch Complex (SLC) 17 at Cape Canaveral Air Station (CCAS) and one pad at SLC 2, Vandenberg AFB (VAFB). The Delta III is only launched from the specially modified SLC17-B pad at Cape Canaveral.

As a launch provider for government missions, Boeing used the Delta II ELV to launch all 24 satellites of the Global Positioning System (GPS) constellation and currently holds an Air Force contract for replacement satellites through the year 2002. The Delta II also successfully launched NASA's Mars Global Surveyor and Mars Pathfinder systems, Mars Orbiter-2, Mars Polar Lander-1, and the recent NASA Stardust probe. Notable commercial Delta II launches involved boosting the majority of the Motorola's Iridium global telecommunications network and initial Globalstar system satellites [9].

The Delta III's maiden launch on August 26, 1998 carried a Hughes Galaxy-X commercial communication satellite and was unsuccessful. Boeing engineers are confident they can prevent the same incident in the future by changing the flight control software [8]. Lessons learned from the first Delta III flight will be used for the basis of improving future launches as part of Boeing's lean practice of continuous improvement and process maturation.

3.3.2 Delta II Operations at CCAS, Florida – A Study in Lean

As with most U.S. industries, it is uncommon to find an aerospace company than can be considered a completely lean enterprise. Nevertheless, many companies are beginning to implement lean practices within their space operations. Boeing is such a company with a goal of implementing lean launch operations ranging in activities from vehicle fabrication to the final lift-off. The following sections are based on the findings of a site-survey performed by the author in November 1998 on Delta II launch operations at Cape Canaveral Air Station and published in the form of a case study. Supporting operational examples in the study are only a small representation of the many lean practices that providers can integrate into their launch operations. While it proved impractical and infeasible for Boeing management to comment on every single activity in the launch process, the examples and philosophies in the case study show how smarter and leaner practices contribute to improving launch operation enterprises.

3.3.2.1 Company Philosophy

As mentioned earlier, the Delta launch system was initially produced and operated by McDonnell Douglas Aerospace until the Boeing-McDonnell Douglas merger of 1997. McDonnell Douglas' published vision from the outset of the Delta program was to be recognized as "an empowered, accountable, flexible, highly responsive, self-disciplined launch team that is committed to being the benchmark worldwide in space launch operations" [33:1]. Included in this empowered launch team are the Delta launch managers, operators, technicians, support crew, and ultimately the customer. While their vision statement is very optimistic, the Delta launch team has implemented significant

organizational and physical changes to their operations while on their journey to become a lean enterprise.

Acceptance to change and improvement are historical parts of the Delta team's corporate culture. The senior launch site manager at CCAS, Philip Payne, nurtured much of the corporate culture in the late 1970's and is considered the father of the Delta's lean concepts of operations. He had a reputation for challenging his team to continually optimize operations flow [34]. Mr. Payne created the current work plan that helped identify and baseline Delta launch operations. He also instilled a strong corporate culture that is still followed by the current launch team management.

Today's Delta launch culture promotes leadership that motivates all stakeholders to achieve the company's goals while focusing on customer requirements. This author could easily sense the confidence Boeing management has in its Delta launch operation system. Perhaps the best test of a company's cultural confidence is allowing a researcher to fully investigate and document their lean processes. A parallel example from the automotive industry is Toyota Motor Company. Toyota was so confident in their lean production techniques that they allowed competitors to make "pilgrimages" to Hiroshima and Toyota City in the late 1970's and 1980's to learn of lean manufacturing and production [47:237].

3.3.2.2 Delta Operational Flow

Before a Delta launch vehicle lifts off from its pad, it undergoes a sophisticated logistics process as portrayed in Figure 11.

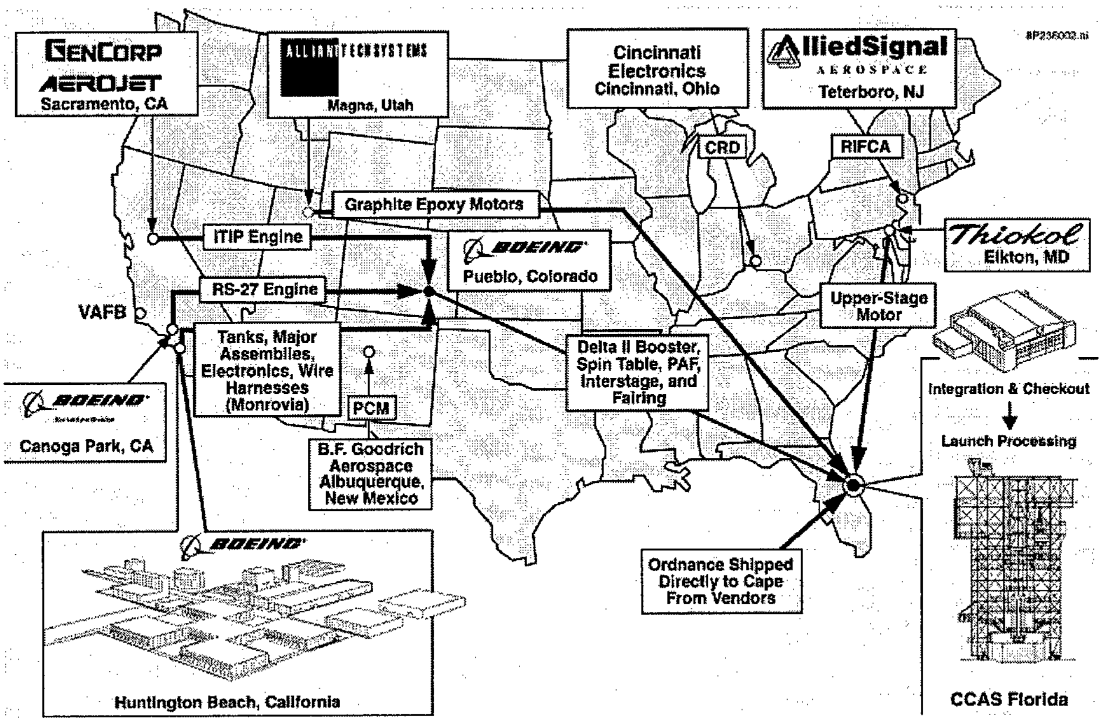


Figure 11 Delta Vehicle Operational Flow (Eastern Range) [17]

Delta launch vehicles are primarily manufactured or processed by four main Boeing divisions. The tanks, major assemblies, and electronics suites are mainly built at the Boeing facility in Huntington Beach, California. The Delta II's staple first-stage RS-27 engine is manufactured at the Boeing-Rocketdyne Division in Canoga Park, California. These major components are then shipped to Pueblo, Colorado where they are mated with the Delta II booster, spin table, interstage, and payload attachment fairing (PAF). Metal fairings are built in Pueblo while composite fairings are built in Huntington Beach. Vehicle and fairings are then shipped to the launch centers where payload integration, checkout, and final launch processing activities are performed.

Boeing's suppliers are integral partners in the process of optimizing vehicle-manufacturing flow. The Delta II second stage engine is built by GenCorp Aerojet in Sacramento, California and delivered to Pueblo, Colorado. The strap-on GEMs are built by Alliant Techsystems in Magna, Utah, and delivered to the final launch site at either VAFB or CCAS. The upper-stage motors are built by Thiokol Systems in Elkton, Maryland and are also delivered to the final launch site. B.F. Goodrich Aerospace in Albuquerque, New Mexico manufactures the Delta II Pulse Code Modulation (PCM) telemetry system. Cincinnati Electronics builds the Command Receiver Destruct (CRD) system while Allied Signal Aerospace in Teterboro, New Jersey manufactures the RIFCA (Redundant Inertial Flight Control Assembly) guidance system. With the exception of the upper stage motors that have a rather long shelf life and are delivered in quantities of three to four, all major sub-systems are built according to the launch manifest and kept by Boeing at minimal to zero inventory amounts [34]. Each set of electronic boxes also has a separate delivery schedule based on launch manifest requirements.

Once the rocket assembly and major vehicle sub-components arrive at their final destinations, they are processed and prepared for launch. The next section highlights the historical changes in the Delta launch processing cycle at Cape Canaveral Air Station that has contributed to reducing the cycle time on the pad from 40 to approximately 21 days. Similar initiatives are in place at the Vandenberg launch facility.

3.3.2.3 Delta Launch Cycle Time Reduction

As mentioned in Section 3.1.1.2, launch cycle on-pad time is probably one of the best and most used indicators of "leanness." Figure 12 depicts the reduction of on-pad workdays for the Delta II since the mid-1980's.

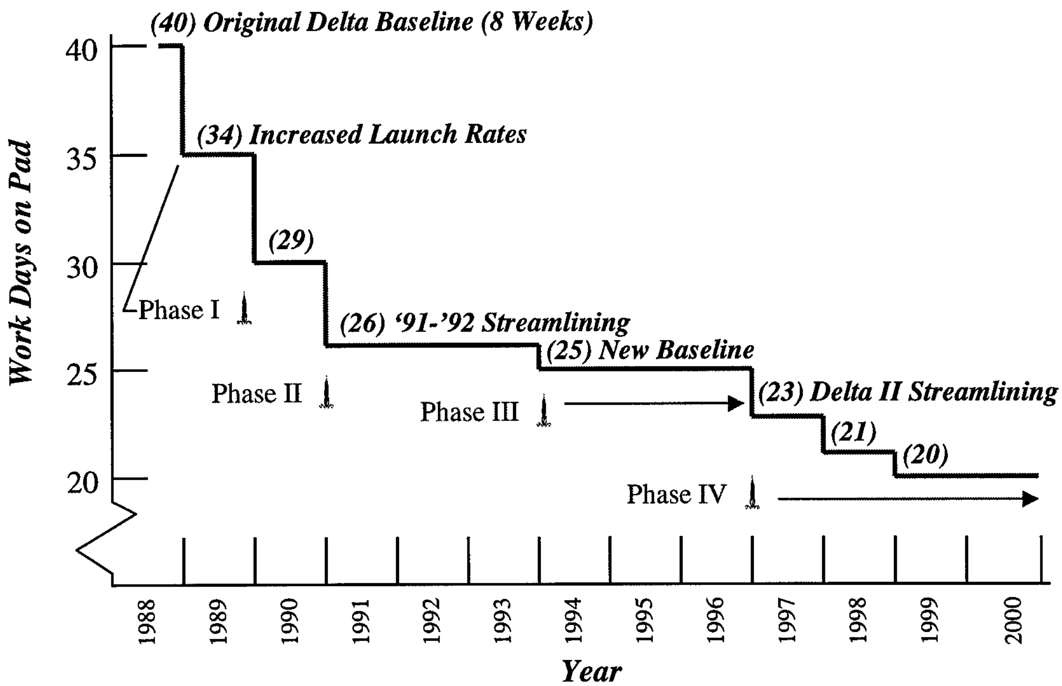


Figure 12 Delta II Cycle Time Capability

One of the major principles in the Lean Enterprise Model (LEM) states that a lean enterprise organization will continuously focus on the customer [32]. In fact, focussing on the commercial customer is becoming the key driver for implementing leaner launch operations for many launch service providers. A significant year for the Delta launch team was 1989. This was the first year of operations for the second-generation Delta II launch vehicle. It was also a year of increased demand due to the initial population of the

NAVSTAR Global Positioning Satellite (GPS) constellation. During this period, McDonnell Douglas began to seriously concentrate on its commercial launch business. The Delta II launched its first commercial payload in 1989. It carried a British broadcasting satellite, the BSB-R1.

In the five years preceding 1989, the extremely low launch rate (approximately zero to three per year) and greatly reduced crew size supported a cycle time baseline of approximately 40 workdays. Crew size was doubled in 1988 to support the move of the Delta's primary mission checkout center from Huntington Beach, California, to Cape Canaveral. This also established an initial launch capability for the GPS constellation. The additional work force allowed the launch processing cycle to be compressed by six workdays, primarily by repackaging more work for expanded second shift operations. This helped decrease the Delta's launch processing baseline to approximately 34 days [34]. More importantly, the initial exercise helped launch operators start to identify, quantify, and optimize the launch-operations enterprise flow. Within a year, manifest requirements mandated even more reductions in the Delta launch processing cycles. Perhaps the best tool that signifies customer "pull" in the launch community is the upcoming launch schedule, or manifest. To meet demand, the Delta management continued with a series of streamlining phases that would incrementally reduce the on-pad time to today's 23 to 21 workday capability. The following sections break down these incremental changes into their streamlining phases and relate them to the Lean Enterprise Model where applicable.

3.3.2.3.1 Phase I Streamlining – Identify and Optimize Operations Flow

In order to pursue new commercial business launch opportunities while still meeting the USAF GPS launch commitments, the Delta management and technician team began a systematic program of cycle time reductions. One of the best lean-enabling practices when identifying and optimizing enterprise flow is to generate models, simulations, and procedures that permit understanding and evaluation of the operational flow process [32]. The Delta team realized this in 1989 and concentrated on analyzing pad qualification and pre-launch procedures. The team then designed smarter test equipment that would run the flight simulations while integrating pre-launch tests off pad when possible. For example, the hydraulics simulation "flights" were moved to the primary Delta Mission Checkout Center (DMCO) at Cape Canaveral where the boosters could be prepped off-pad. The DMCO usually has two horizontal boosters that are "on deck" and are prepped for launch while two more boosters occupy the launch pads. Since the unassembled boosters occupy floor space at DMCO early in their launch cycle, they present perfect opportunities for early inspection and testing.

In the first year of the Phase I, procedural changes associated with navigation and control system testing reduced on-pad time by one work week, from 34 days to 29 days [34]. Additionally, many of these tests were moved off-pad to DMCO. Before relocating these tests to DMCO, technicians had to break into launch-qualified systems on the pad to test the navigation electronics and gyros.

Phase I improvements ultimately allowed the Delta team to further identify and optimize their operations flow. During this first-cut streamlining phase, the team was able to shave five days from the launch-processing schedule.

3.3.2.3.2 Phase II Streamlining – Infrastructure/Facility Improvements

As part of Phase II streamlining objectives, the Delta team reconsidered the way it processed the crucial pressure systems in the Delta II vehicle. The vehicle's second stage is comprised of a pressure-fed system that depends on two high-pressure subsystems. The first is a 4,350 psi (29,992 kPa) helium-gas system that is regulated to approximately 260 psi (1,792 kPa) to drive the propellants (Aerozine 50 fuel and N204 oxidizer) into the engine. The second is a 4,350 psi (29,992 kPa) nitrogen-gas system regulated to 275 psi (1,896 kPa) that feeds the redundant-attitude-control-system (RACS) to provide roll control during powered flight and roll, pitch, and yaw control during unpowered flight. Before the streamlining process, these systems were checked and tested on the launch pad. If they failed during testing, technicians would have to unbraze and disconnect the pressure tubing and fittings that were welded onto the vehicle. The Delta system uses an ultrasonic brazing process that flows a liquid alloy through fittings to permanently braze the system shut, thereby preventing leaks and failures during flight. Of course, tearing into a flight-ready vehicle to repair a failed test is unfavorable and introduces risk into other sub-systems as well as infusing unnecessary retest days in the launch flow. Furthermore, high-pressure leak-checks are deemed hazardous operations and require "clear-pad" conditions that preclude completion of any concurrent work on the pad.

Testing of these systems alone required three days, two of which were under clear-pad conditions.

To eliminate the unfavorable circumstances of testing the second stage pressure systems on the pad, a separate Area 55 high-pressure test facility was built to run the required pre-launch propulsion leak and flow tests. High-pressure tests can now be performed before the vehicle is assembled. This reduces vehicle on-pad time, and allows technicians to test crucial pressure systems early in the launch processing cycle. Any necessary repairs are now performed without endangering other launch system timelines. Figure 13 identifies the flow of flight hardware to Area 55 and other launch processing facilities at Cape Canaveral.

In addition to the high-pressure test facility initiatives, the Delta team reviewed how they ran pad qualification tests for each mission. Before Phase II streamlining, the launch vehicle's transducers and sensors were calibrated to the mission control facility (or "blockhouse") while the vehicle was on the launch pad. After reviewing these practices, the team designed first and second-stage simulator algorithms to test and calibrate the vehicle with blockhouse systems before the vehicle is erected on the pad.

As a result of Phase II improvements, the Delta team was able to move hazardous and time consuming pressure tests to a separate facility, design a sensor simulation and calibration system, and ultimately remove three additional days from the overall launch processing flow cycle.

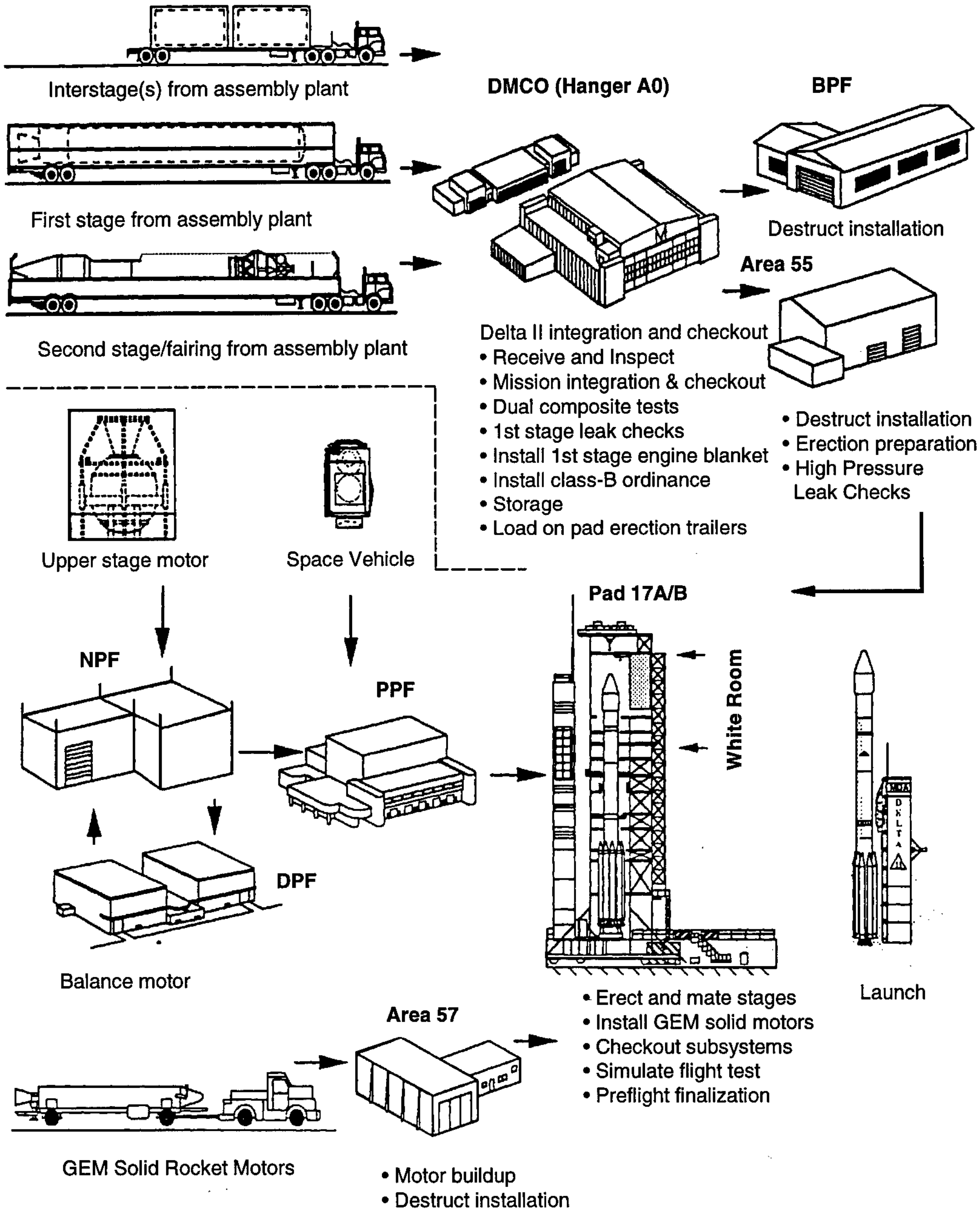


Figure 13 CCAS Launch Site Flight Hardware Flow [33]

3.3.2.3.3 Phase III Streamlining – Continued Optimization

In their pursuit of reducing the number of workdays on the launch pad to meet growing customer demand, the Delta team continued to optimize its operational flow. By the end of Phase III, all candidate streamlining operations were either moved to the DMCO or high pressure test facilities. Furthermore, the team incorporated improved support equipment and started construction of a new launch support facility that integrated the latest in state-of-the-art mission equipment. The new launch support facility at Cape Canaveral Air Station was also designed in conjunction with similar facility upgrades at the Delta site at Vandenberg Air Force Base. The new launch infrastructure was built with efficiency and commonality in mind. The terminals, commands, and workstations are identical for each site. These common elements help promote lean operations by maximizing stability in a changing environment such as the launch business.

Phase III streamlining initiatives also continued to bring incremental value-added improvements to the launch enterprise flow. After each change to the flow, the Delta team continued to reevaluate the value stream to identify even more opportunities for improvement. For example, after determining that first stage leak checks could be run at pressures that were not deemed hazardous, the team moved the tests back from the pad to DMCO. Also the installation of Class B ordinances was considered safe enough to move off-pad to DMCO and the booster processing facility (BPF). (Class B ordinances are small pyrotechnic devices that initiate launch sequences during flight. They have minimal firepower and considered safe enough to install in a populated area.) This

allowed technicians to place the pyrotechnics in their appropriate locations before the vehicle is moved to the pad. For example, the first-stage gas generator that spins up the turbopump at launch is initiated with a small Class B pyrotechnic ignition device. It is now easier to install this device in the first stage at DMCO before the vehicle is assembled and shipped to the pad.

Phase III streamlining initiatives allowed the Delta team to continue to optimize their operations flow and ultimately removed two more days from the launch-processing schedule. The new on-pad benchmark is 23 workdays instead of the original 40 days prior to the streamlining initiatives.

3.3.2.3.4 Phase IV Streamlining – Continued Operability Improvements

Delta streamlining is currently in Phase IV. Twenty-three days on-pad time is the present benchmark with some missions dipping to 21 days. Phase IV initiatives are manifested by continuous improvements to launch operations and the constant reassessment of the launch processing flow. This lean practice ensures continued realignment of the value stream that manages flow. The Delta team is constantly reviewing the launch process steps and seeing where they can focus new procedures towards the proper utilization of people and time. One method includes reassessing work shifts and associated activities. An example is using the second shift of technicians to not only break down first-shift test equipment and set up tests for the next day, but to also run short tests in the sequence that night themselves. Another case includes combining tests and preparation procedures where applicable. For instance, three successive vehicle preparation and checkout tests were evaluated for consolidation. The simulated system

flight test was run twelve days before launch. The engine sequence tests and preparations were then run the next day. Finally, the first stage RP-1 fuel qualification tests were run on the third day. The Delta team reviewed the procedures, calculated time and manpower requirements, and determined it would be feasible to reduce processing by one day by combining the engine sequence tests with simulated flight and engine preparations for RP-1 qualifications.

Another example of incremental flow optimization in Phase IV is where the Delta team revised the procedure for installing the first-stage engine blanket. The blanket is attached to the engine before launch to thermally protect the vehicle during flight. This blanket was initially installed on the pad and, as with most custom-fitted cloth devices, could easily tear or fit improperly upon installation. The Delta team determined they could move this procedure to DMCO where technicians would have more time to install the blanket. The technicians at DMCO then stated that their system tests were unimpeded by the blanket and it could be installed at the assembly factory in Pueblo, Colorado. After further evaluation, the Delta team in Pueblo decided that the supplier, Rocketdyne, should install the blanket at the engine factory itself. Installing the blanket at Rocketdyne not only streamlined processing procedures, it also eliminated inventory at the Delta installation facilities, reduced the logistics stream, and allowed technicians at the launch sites to concentrate on more important tasks. The engine-blanket scenario is a simple example of the importance of lean thinking. Analyzing flow, reevaluating operations sequence, and driving a procedure back to its earliest opportunity shows how launch operators can optimize procedures and continue ensuring processing capability and maturation.

While the previous Phase IV optimization examples may seem too obvious and logical to mention in a case study, they represent the power of understanding one's enterprise system. Such examples can only be obvious if management has a solid understanding of all the activities in an enterprise and can identify what are the value-added procedures that increase flow. One may make the analogy that it is only possible to finely tune a machine that is tuned in the first place.

3.3.2.3.5 Phases I-IV LEM Assessment

While most Delta flow-reduction practices in Phases I through IV are very launch-system specific, they serve as an example of the steps necessary for a team to start building a lean operations enterprise. To the Delta team's credit, they were able to eventually redesign and optimize an operations flow that had been impeded by wasteful launch procedures for decades. Before it embarked on the seemingly insurmountable task of process flow optimization, the Delta team understood the importance of the first step to develop a lean enterprise, *identify enterprise flow* [32]. Upon further evaluation of the case study, many of the Delta practices can be directly applied to the Lean Enterprise Model. Table 4 lists the enabling LEM practices (as depicted in Appendix B) employed by the Delta team as they identified and optimized the Delta II launch operations enterprise flow. The table also lists supporting practices and metrics as they may also be applied to the LEM.

Table 4 Delta II Flow Identification and Optimization Practices

Enabling Practices	Suggested Supporting Practices	Suggested Metrics
• "Establish models and simulations to permit understanding of the flow process"	• Simulate pad qualification and pre-launch operations	• Launch Rate • Work Days on Pad • Hours per launch processing activity • Number of personnel required to complete a launch activity • Number of on time launches • Schedule slips • Increased launch availability
• "Reduce the number of flow paths" • "Strive for single piece flow"	• Determine which launch activities feed subsequent activities. Restructure sequence accordingly to reduce "backflow" • Run pre-launch tests off pad • Drive component testing to earliest opportunity possible in flow • Program high-risk procedures off-pad and off the process' critical path	
• "Minimize inventory through all levels of the value chain"	• Minimize inventory at launch site. Drive back to supplier if possible. *(e.g. The Delta II's first stage engine blanket scenario)*	• Number of inventory items on site
• "Synchronize production and delivery throughout the value chain," *(or in the launch operations case, synchronize launch activities to the launch manifest)*	• Configure flow to meet launch demand	• Measure *takt* time for each processing activity

3.3.3 Delta Post-Production Assembly and Test Philosophy

The previous four-phases of launch operation improvements show how the Delta team initiated steps in becoming a truly leaner enterprise. It accomplished many of these activities before concepts of lean thinking were ever established. Nevertheless, the team realized they had to first focus on the significant tasks of *identifying and optimizing* the launch enterprise flow before considering other aspects of launch. While the four optimization phases concentrated mainly on one aspect of the Lean Enterprise Model, they would have not been successful if the Delta team had not considered other lean principles in the overall launch enterprise. The launch-cycle reduction procedures were ultimately effective because all stakeholders subscribed to the processes and accepted changes in their launch routines. Lean process initiatives are only beneficial if a corporate culture and its underlying philosophy can embrace, communicate, and delegate proper authority for change in the management chain. Everyone in the organization must eventually agree on a standard of practices that drives the corporate culture. The following sections highlight the underlying philosophies the Delta team applies in its launch operations enterprise [34].

3.3.3.1 Maintain a Single Standard of Quality

Boeing's published policy is to maintain a single standard of quality for all customers at the Pueblo production facility and both launch sites [34]. This standard is designed to achieve maximum launch success in the most cost-effective manner. One appropriate example is the use of government quality monitors. Launch providers are required to pay government monitors at production facilities to inspect the vehicle

systems that will launch government payloads. Boeing has chosen to have the government monitors inspect all launch vehicles and parts regardless of payload ownership. Company management feels that the additional costs for inspectors are hardly noticeable in the bottom-line especially when they feel it's a small price to pay for a single standard of quality [34]. Cost savings while maintaining a single standard can be additionally realized in the reduction of logistics stores and associated paperwork. Maintaining a single quality standard also imparts flexibility in launch vehicle logistics when, if necessary, vehicles scheduled for government payloads can be substituted with commercial vehicles.

3.3.3.2 Maximize Continuity and Commonality

Wherever possible, the Delta team attempts to maximize and optimize assembly and test-flow continuity from the production facilities to the launch sites and within the launch site processing facilities. This helps to avoid "backflows" in the process flow stream. An excellent example of this is the incremental process streamlining objectives discussed in the previous sections that allowed the Delta team to restructure its launch operations enterprise. Launch operation activities were placed in sequence to maintain a direct flow while minimizing opportunities for backtracking or rework.

The Delta team also places a high value on maintaining commonality between the launch sites for all launch vehicles. This provides flexibility of operations for both government operators and the Delta launch crew, reduces costs of employing and maintaining separate systems, streamlines training, and maximizes stability in a high-tempo environment. For example, Boeing trains their launch teams at both launch sites to

act as "tiger teams." If necessary, the cross-trained tiger teams can augment each other at both Cape Canaveral and Vandenberg launch facilities. To ease operations and reduce confusion, the consoles in each launch control facility are also similar, using common labels, data displays, and procedures. Even launch site preparation documents (LPDs) are common down to their methodology of labeling. For instance, the guidance-control-qualifications launch preparation document is labeled F15 ('F' denoting 'Florida' and '15' denoting days before launch) at Cape Canaveral and V15 at Vandenberg. If procedures are different for each launch site, the changes are plainly marked and explained in the launch preparation documents. The Delta team's use of LPDs is explained in more detail in Section 3.3.3.4.2.

3.3.3.3 Structure and Optimize Test Plan and Procedures

The philosophy of structuring and optimizing the launch test plan has been the main driver for reducing workdays on the launch pad. The test plan in pre-launch processing plays a very significant role in flow operations. If the test plan is optimized appropriately, then operations flow times are decreased accordingly. To make tests more efficient, the Delta team pursues the following philosophies.

<u>3.3.3.3.1 Structure Test Plan to Test at First Opportunity</u>

As shown earlier in the engine-blanket scenario, structuring a plan to accomplish testing at the location where final configuration is first established (factory, off-pad, or pad) can produce favorable results and minimize unnecessary repetitive testing. Delta technicians also accomplish post-installation continuity, resistance, and isolation measurements of flight electrical harnesses at the production facility prior to launch site

delivery. These and other tests that require tight tolerances have been moved back in the processing cycle to their initial production locations. Consequently, bad parts can be removed early in the assembly line before additional components are added, welded, or permanently affixed on the vehicle. Identifying bad parts early also allows technicians familiar with the part to troubleshoot the problem and contact the supplier to discuss ways that avoid failures in the future.

Another example of structuring the launch test plan includes running leak tests on all fluid connections immediately after assembly. The pad is the worst place to run these tests and certainly a poor location for technicians to be creative if a failure occurs. Subsystem tests on the pad may require disassembly of a flight ready vehicle and potentially risk compromising other systems. If such tests fail, complicated repairs can even cause more damage to the vehicle and may ultimately delay the launch date. Again, designing a test plan to reduce final testing at the pad requires detailed knowledge of the overall launch operations flow.

Additionally, structuring the test plan early also allows the launch team to verify mission specific modifications, including software changes, prior to delivery to the launch pad. This flexibility is important since no two missions are alike. Payloads may be dissimilar, and the Delta II rocket itself comes in varieties of 2-stage, 3-stage, and may include three, four, or nine strap-on solid rocket motors. Waiting until the pad to see how a particular vehicle configuration will affect the launch did not make sense in the past, and it certainly does not make sense in today's lean launch enterprise.

3.3.3.3.2 Deliver Hardware to the Pad at Highest Level of Integration

Today's ELV stages and payloads are still assembled on the pad. The current infrastructure is not designed to erect a vehicle and its payload on the launch pad in a similar fashion as the Russian Proton. Future EELV stages will be assembled and tested off-pad, moved to the launch pad by a transporter-erector, and erected as one ready-to-launch vehicle. In the meantime, the Delta launch team is ensuring the Delta II is delivered to the pad at the highest level of integration practical. The vehicle is still fully assembled (minus payload) in DMCO to verify electrical connections. It is then subjected to a generic flight-test program to verify the flight systems. The systems are then disconnected and the stages brought to the pad. The purpose of verifying the systems at DMCO is to prevent them from being connected for the first time at the launch pad.

Once on the launch pad, a flight systems end-to-end test is run to check the flight performance of the fully integrated vehicle including the payload, flight, and ground software. Unlike the flight test program at DMCO that used generic flight parameters, the second test on the pad is tuned with algorithms rewritten to demonstrate the complete mission with actual flight values. This gives the Delta team full confidence of the upcoming launch and allows them to correct any anomalies they may encounter.

3.3.3.3.3 Plan for Contingencies Within Flow

In addition to optimizing the launch operations flow, the Delta team has generated a risk management strategy that realistically plans for contingencies and considers time factors and breaches in systems integrity during test sequences. Under the LEM

overarching practice, *implement Integrated Product and Process Development (IPPD),* an associated enabling practice is for the operator to define risk management [32]. Defining risk management for some may be as difficult as defining value. As with the definition of value, it is the process stakeholders who must classify their view of risk management and determine how it directly applies to their operations. Some companies may require complete risk avoidance rather than accepting a small amount of risk within the enterprise environment. Many who understand the technical nature of the launch business would state that risk avoidance is practically impossible. However, it is the launch provider's responsibility to determine its level of risk acceptance in the launch process and isolate the systems or activities that may result in contingencies. If it is technically infeasible or prohibitively expensive to fully eliminate those contingencies, the launch providers must build plans and procedures to ensure that a launch vehicle will be fully operational within the shortest amount of time. The Delta team maintains such procedures in a library of contingency documents that cover examples from changing out defective black boxes to replacing hydraulic actuators. As with optimizing an operations flow, preparing for contingencies also requires a strong understanding of the launch enterprise and all related factors.

It is interesting to note the philosophy the Delta team has with planning contingency time. While other launch providers may schedule in a 10% - 25% cushion for unforeseen events, the Delta team instead schedules their launch processing to account for full use of resources and protects itself by a system that is designed to rely on minimal dependencies. Basically, instead of planning contingency time, the team builds contingency plans through good risk management and a flexible flow structure. If extra

time is required, the team will increase the operational tempo to meet demand, but it never initially plans for takt times that may be easily expanded to fill an inflated launch schedule.

3.3.3.3.4 Employ Proper Data Management Principles

The Delta team's philosophy is to maintain a lean database of data collected during launch processing. Specifically, technicians and engineers only collect data that they plan to ultimately review and use. Optimizing the data flow also ensures a seamless information stream that guarantees all launch operators have access to organized, available, and traceable data.

3.3.3.4 Additional Practices

The previous sections highlight the overarching philosophies the Delta team employs to continuously improve their launch operations enterprise. Many of Delta II improvements have been in place before Boeing or McDonnell Douglas heard of the Lean Aerospace Initiative. Still, the improvements show that a company committed to quality and its customers can implement business practices that ultimately manifest themselves as lean practices. In addition to the published philosophies and practices in the previous sections, there are additional lean-enabling trends within the Delta team's corporate culture.

3.3.3.4.1 Promote Lean Leadership

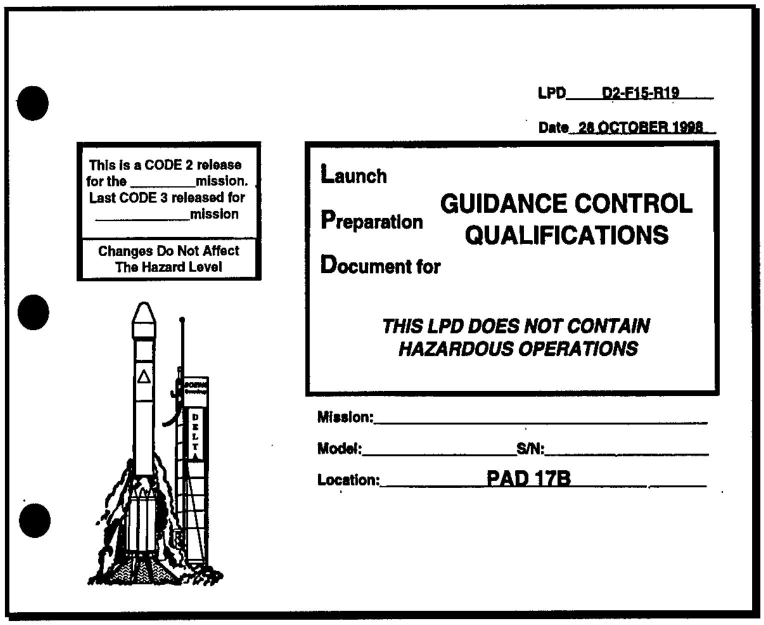
The Delta team promotes lean leadership at all levels. Every stakeholder on the team from the launch site manager to the technicians on the pad is involved in achieving

an optimized launch operations enterprise. Each morning the launch team, payload customer, and their Air Force partners have a "stand-up" meeting where launch status is communicated to every member on the team. Sessions are video teleconferenced to the pad, blockhouse, and operations center. These meetings are very thorough and every team member has an opportunity to report on progress, conflicts, and overall status. This system helps ensure consistency and focuses on the launch plan while involving every stakeholder in the process.

3.3.3.4.2 Launch Preparation Documentation

The Delta team has also built a system that assures seamless information flow to all technicians responsible for launch processing. This system is manifested in daily test procedures called launch preparation documents (LPDs). The revolutionary LPD system was created by Boeing to effectively streamline the Delta's processing documentation. While LPDs may not seem exceedingly remarkable to aircraft maintainers who are accustomed to a flight-line's Technical Orders (TOs), it is important to note that launch operations are very different than aircraft operations. Both the aircraft and space industries are diverse and it is sometimes difficult to draw parallels between the two. Building a system of "technical orders" for launch vehicles is an example of looking to other enterprises for smart ways to optimize one's own process. As with aircraft TOs, the Delta launch preparation documents standardize system configuration control while communicating a single standard of procedures that an appropriately trained operator can employ. Each stand-alone LPD includes any blueprints, procedures, and checklists

necessary to complete a given day's task. A cover of a sample LPD is depicted in Figure 14.



LPD D2-F15-R19

Date 28 OCTOBER 1998

This is a CODE 2 release for the ________ mission. Last CODE 3 released for ________ mission

Changes Do Not Affect The Hazard Level

Launch Preparation Document for

GUIDANCE CONTROL QUALIFICATIONS

THIS LPD DOES NOT CONTAIN HAZARDOUS OPERATIONS

Mission: ________

Model: ________ S/N: ________

Location: PAD 17B

Figure 14 Example Delta II Launch Preparation Document

Even the LPD cover helps reduce confusion and communicates the document's objective. The document in Figure 14 is labeled "D2-F15-R19." This states that the LPD's guidance and control qualification procedures are for the Delta II, intended to be performed fifteen days before launch at the Florida (hence the 'F' designator) site, and that the document is in its nineteenth revision. The cover of the LPD is also color-coded orange for commercial payloads or blue for government payloads. Each LPD is essentially a checklist of procedures to help make complicated launch processing instructions easy to follow. To maximize data traceability and accountability, a LPD is signed off upon completion by the test conductor, assistant test conductor, and responsible engineer. The documents also provide a common and consistent means to

record progress and metrics for a given task. These metrics can then be gathered and used within statistical sets to determine efficiency, resource utilization, or flow time. Ultimately they can be used as tools and indicators for continued flow optimization.

Managers also challenge each stakeholder to improve the launch process through the LPD system. At the end of each LPD is a detailed recommendation sheet. Every technician is encouraged to write suggestions that can improve their procedures. These recommendations may then be incorporated in the next mission's documentation. Stakeholders are also encouraged to author LPDs that are completely new or consolidate a set of LPD activities. The Delta team has published a "Friendly Writers Guide to LPDs" that ensures commonality and consistency between new LPDs while walking the writer through the documentation process [34].

The LPD system maximizes flow visibility and streamlines a complicated and technical process. It also allows management to baseline their training program around a common set of procedures and optimize allocation and utilization of people. The inventor of the LPD process probably did not realize his revolutionary system represented lean principles in so many ways.

3.3.3.4.3 Government-Contractor Interaction

Interaction between Boeing and its Air Force partner, the First Space Launch Squadron (1SLS), has become a key element for launch success. The teams work hand-in-hand to ensure maximum use of space assets. Each team appears to trust one another and lacks the tension many government organizations and their contractors seem to endure. This display of trust is an important factor to cultivate in today's shrinking

defense force, and is especially important now that acquisition reform initiatives are requiring less oversight from the government. Air Force Space Command is in the process of transitioning from an oversight role to an "insight" role where the government is attempting more of a hands-off approach to launch management [19]. General Robert C. Hinson, Director of Operations for Air Force Space Command states, "We are now concentrating on gaining insight with our launch contractors rather than providing oversight." Commenting on the need to optimize military manpower levels at the launch squadrons, he remarks, "We have blue-suit maintenance people who never touch a wrench, operators who never touch a booster. In a time of declining manpower we feel this is not the most efficient use of our highly trained people. [19]" Before transitioning to a new insight role, it will be important that launch providers show they are committed to their customers and build launch enterprises that ensure efficient access to space. It will be the government's responsibility to properly evaluate such enterprises and reward the providers who successfully meet mission assurance requirements, reduce costs, and deliver payloads with maximum success.

3.3.3.5 Delta Launch Operations and Test Philosophy - LEM Assessment

Within the Delta II team's post-production assembly and test philosophy are combinations of Lean Enterprise Model overarching and enabling practices. To illustrate results of the case study, tables in this section summarize enabling LEM practices as they apply to the Delta II team's operation procedures and organizational culture. Each table also lists supporting practices and metrics as they may be applied to the LEM.

Table 5 concentrates on the LEM practice of *ensuring process capability and maturation.* While it appears this practice was originally drafted by the LAI consortium to be applied in design and manufacturing processes, it is also well suited for system operations. The table also lists applicable Delta II lean practices as they can be applied to the existing LEM enabling practice of ensuring process capability and maturation, and recommends additional enabling and supporting practices as they may be applied to launch operations.

Perhaps two of the most important aspects in the Delta launch team philosophy are communications and information flow. For highly technical processes such as launch operations to be successful enterprises, seamless information flow is required among all stakeholders whether they are the process technicians, operations management, the launch operators themselves, customers, or hardware suppliers. Table 6 describes how the Delta II launch process may be applied to the LEM enabling practice of *assuring seamless information flow* among all stakeholders in the launch enterprise. It also lists recommended supporting practices and metrics that may be applied to operation enterprises.

Table 5 Delta II Flow Process Capability and Maturation Practices

Enabling Practices	Suggested Supporting Practices	Suggested Metrics
• "Define and control processes throughout the value chain" - LEM	• Structure operations test plans and procedures to avoid "backflow" in launch processing (i.e. test the right part at the right time.) • Deliver launch hardware to the pad at the highest level of integration	• Number of re-tests • Number of flight-ready parts compromised by testing procedures or failed tests • Number of electrical connections that need re-testing on pad after complete vehicle assembly
• *Suggested Practice:* Maintain a single standard of quality (Single Process Initiative)	• Optimize use of government or company quality inspectors • Avoid flight systems being classified as either "commercial" or "government." Apply same level of quality assurance	• Number of system inspectors within process flow • Number of system or sub-system failures
• *Suggested Practice:* Maximize continuity and commonality of operations *(Note: may also be applied to LEM overarching practice, "Optimize Capability and Utilization of People")*	• Build common mission support, range, and operation systems regardless of launch site • Design identical launch processing procedures regardless of site • Build a generic training plan that provides flexibility in the training of operators that covers all operations sites	• Number of unique range items, procedures, or infrastructure items that require modifications to a common operations plan • Number of documented differences in processing or operations procedures for each site • Increased launch rate

Table 6 Delta II Information Flow Practices

LEM Enabling Practices	Suggested Supporting Practices	Suggested Metrics
• "Make processes & flows visible to all stakeholders"	• Combine and document launch process activities in standard configuration control system [such as the launch preparation documents (LPDs)] • Provide training for creation of improved documentation as flow process is optimized and activities changed or combined	• Amount of documentation per set of activities (ex: (1) LPD for each workday) • Number of launch processing activities consolidated per document • Number of contingency plans integrated documentation • Percent commonality among documentation • Document information retrieval time • Number of comments generated by launch technicians that suggest process improvements
• "Establish open and timely communications"	• Maintain open communications with launch hardware suppliers. Continuously communicate ways to optimize flow *(e.g. the Delta II first stage engine blanket scenario)* • Initiate launch status "stand-up" meetings to include all launch stakeholders	• Percent of stakeholders involved in communications *(goal: 100%)* • Number of stakeholders required to report at predetermined intervals within flow process

Table 6 Delta II Information Flow Practices, Continued

LEM Enabling Practices	Suggested Supporting Practices	Suggested Metrics
• "Minimize documentation while ensuring necessary data traceability and availability"	• Generate data system to require user inputs that facilitate gathering essential flow statistics and related metrics *(e.g. LPD fields that require measurement inputs of flow time, resource utilization, etc)* • Assure process ownership and accountability within documentation *(e.g. require technicians to sign off on tasks at the end of each activity)*	• Percent of documentation signed-off at the end of each activity series • Percent of data inputted in documentation that is used for later analyses

Based on the preceding analyses of the Delta II launch operations process and its relation to the LEM, it is rather easy to see which lean principles are significant drivers in the Delta II launch operations philosophy. Furthermore, additional Lean Enterprise Model practices stand out in the Delta II team's launch operations. Table 7 combines several of these results and lists recommended supporting practices and metrics where applicable to the LEM.

Table 7 Additional Lean Practices in the Delta II Launch Enterprise

LEM Overarching Practices	LEM Enabling Practices	Suggested Supporting Practices	Suggested Metrics
• "Continuously Focus on the Customer"	• "Provide for continuous information flow and feedback with stakeholders"	• Initiate regular status meetings with all launch stakeholders, including payload customer	• Positive performance survey results • Performance evaluation on award fee determinations
• "Promote Lean Leadership at all Levels"	• "Flow-down lean principles, practices, and metrics to all organizational levels" • Instill individual ownership at all levels	• Build lean practices into operations activities, document required procedures in operational checklists • Build in accountability into process. Require applicable stakeholders to sign off activities in launch documentation	• Develop lean metrics at all levels
• "Develop relationships based on mutual trust and commitment"	• "Build stable and cooperative relationships internally and externally" • "Provide for mutual sharing of benefits from implementation of lean practices"	• Include suppliers in optimizing lean operations flow • Build a teaming relationship with local Air Force launch squadrons • Focus and document shared mission of providing cost-effective, safe, reliable, and flexible access to space	• Level of mission readiness at launch site • Positive performance survey results • Performance evaluation on award fee determinations
• "Maintain challenge of existing processes"	• "Establish structured processes for generating, evaluating, and implementing improvements at all levels"	• Optimize data flow • Collect only launch data planned for later review and use	• Percentage of data collected that is ultimately used

4 Future Lean Initiatives

While the previous sections describe how lean principles are being applied to current launch operations enterprises, this chapter provides a brief survey of future programs that are intended to make Air Force launch operations "better, cheaper, and faster." To the degree each program takes advantage of lean principles will depend on system designers and ultimate operators.

4.1 EELV

In addition to improving existing launch operations, two U.S. launch providers are ramping up production for the next generation of evolved expendable launch vehicles (EELV). The EELV program is designed to reduce current launch costs by at least 25%, with an objective of 50%. Table 8 lists cost and other Air Force EELV requirements.

In December 1996, the Air Force awarded initial launch service contracts to Lockheed Martin and Boeing for development of the EELV. After the two EELV concepts were presented, the Air Force announced contract awards on October 16, 1998. It awarded Boeing a procurement contract of 19 Delta IV EELV launches valued at approximately $1.38 billion [36]. To maintain its dual EELV acquisition contract strategy, the Air Force also awarded a contract to Lockheed valued at approximately $1.15 billion to complete development of its EELV and to provide launch services for nine missions between the years 2003 and 2005 [35].

Table 8 EELV Requirements Matrix [4:23]

Requirement	Threshold	Objective
Mass To LEO	17,000 lb_m (7,711 kg)	+15%
Mass To Polar Orbit 1	4,400 – 7,000 lb_m (1,996 – 3,175 kg)	+15%
Mass To Polar Orbit 2	41,000 lb_m (18,597 kg)	+5%
Mass To Semi-Synchronous Obit	2,500 – 4,725 lb_m (1,134 – 2,143 kg)	+15%
Mass To GTO	6,100 – 8,500 lb_m (2,767 – 3,855 kg)	+15%
Mass To Molniya Orbit	7,000 lb_m (3,175 kg)	+15%
Mass To GEO	13,500 lb_m (6,123 kg)	+5%
Vehicle design reliability	98%	>98%
Standard launch pads	Able to launch all configurations	Same
Standard payload interface	Standard payload interface for each vehicle class	One standard payload interface
Cost Savings: Reduction over current systems	25%	50%
Timeliness: Probability of launch within 10 days	80%	90%
Responsiveness:	45 Days (Medium EELV) 90 Days (Heavy EELV)	30 Days (Medium EELV) 60 Days (Heavy EELV)
Launch Rate: During 12 month period	14	26

While Boeing and Lockheed Martin EELVs share the common goal of reducing existing launch costs by 25% to 50% and meeting future responsiveness requirements,

both vehicles differ slightly in their technological designs. For example, the Boeing EELV will be powered by a new Rocketdyne propulsion system, the RS-68 liquid oxygen/hydrogen fueled rocket engine. The RS-68 will generate approximately 650,000 lb_f (2,891,340 N) of thrust at lift-off and will be the most powerful liquid oxygen/hydrogen rocket engine in the world [6]. The driving force behind the new lean RS-68 design was to use three-dimensional modeling tools to reduce engine parts count, thereby reducing engine costs [39]. The Lockheed EELV main propulsion system is based on a re-engineered version of a liquid oxygen/kerosene rocket engine originally developed in Russia and is similar to the one used on the Proton launch vehicle. This engine, the RD-180, is part of a common core booster that will be first flight-tested on Atlas III launch vehicles. One interesting technological note is that the RD-180 is the world's first expendable liquid-propellant engine that can be throttled, thereby providing increased flexibility in planning launch profiles [38]. Regardless of the technologies used in the two competing EELV designs, both EELV contractors are planning to implement leaner practices in their production and operations. The following sections briefly highlight the practices Lockheed Martin and Boeing will use in their EELV launch operation enterprises.

4.1.1 Lockheed Martin EELV Operations Plan

Unlike the current Atlas II family of expendable launch vehicles, all major launch processing operations of Lockheed Martin's EELV will be completed off-pad. Lockheed planners are working towards a "clean pad" concept of operations that should drive EELV delivery-to-launch cycles down to approximately 21 days (with only one day on

the pad), increase launch rates by 50%, reduce launch costs 25 to 50%, and require 33% less people for launch processing operations [28]. Lockheed's clean-pad concept is similar to the Russian Proton processing practices in many ways. For example, the concept allows payloads to be processed in "offline-encapsulation" facilities (instead of the pad) and mated to EELV boosters in another separate processing facility. The entire system will then be transported to the pad as a single ready-to-launch unit [38]. With optimistic scheduling a vehicle could be rolled out to the pad 24 hours before launch, with on-pad fueling consuming only one 8-hour shift [38].

In an attempt to drive all system checkouts as far back as possible in the operations flow, major system verification tests will be completed at Lockheed's Denver, Colorado manufacturing facility. In an attempt to optimize overall flow for both payloads and launch vehicles, Lockheed plans to synchronize production and delivery throughout the company's value chain. Since Lockheed produces many of today's satellite payloads, it plans to synchronize future delivery of rocket boosters with their payloads. As a result, the company intends to cut overall cycle times between sale and delivery of complete systems. Nathan J. Lindsay, Lockheed Martin vice president and EELV program manager, told Aviation Week, "It doesn't make much sense to have an 18-month satellite cycle time and a 24-month rocket cycle time" [38]. He also states the company has implemented an Integrated Product Team (IPT) management structure at the factory to bolster systems engineering capabilities that can further reduce manufacturing cycle times [38].

4.1.2 Boeing Delta IV/EELV Operations Plan

The Boeing Company's EELV design concept was to start clean and develop manufacturing, processing, and launch facilities with lean practices in mind from the beginning of conceptual design. Boeing has built a dedicated EELV manufacturing facility in Decatur, Alabama, which provides water access for the transportation of its new boosters to both Cape Canaveral and Vandenberg launch sites. The Decatur plant was designed from the ground up to use a new lean manufacturing system and is directed by a "lean manager" [5]. To continue practices first learned with the Delta II launch processing system, Boeing plans to push more integrated checkout procedures of major EELV subsystems to the Decatur plant [39]. Once at the launch site, Boeing will process the vehicle horizontally instead of traditional vertical stacking practices. This will save on new building costs and should result in safer processing operations [39]. Boeing plans to process as many as three launch vehicles at a time and will roll each mated EELV first and second stages to the pad and erect them vertically. The payload, its fairing, and booster adapter will already be checked out when they are hoisted to the bottom two stages on the pad. Boeing estimates that major components could arrive at the launch site within 30 days of launch. Once at the site, on-pad time for the first and second stages should last approximately six days [39].

4.2 Range Standardization and Automation (RSA)

While U.S. launch sites are preparing to host new EELV systems, the Air Force will also be implementing its Range Standardization and Automation (RSA) program.

The RSA program is designed to address and rectify two main launch deficiencies. The first is unresponsive spacelift and the second is costly, inflexible launch ranges. The RSA program consists of major upgrades to aging range operation systems and tracking equipment and is designed to improve range reliability, availability, maintainability, and operability. Through these upgrades, the Air Force is expecting to significantly reduce operations and maintenance costs. The following activities are planned during the RSA program:

- Consolidate instrumentation using unified tracking antennas at remote tracking sites. This will consolidate metric, telemetry, and command functions at both the ETR and WTR remote tracking sites.

- Upgrade the Cape Canaveral communications backbone with a fiber optics network to allow redundant communications capabilities, increased data rate and bandwidth, and increased communications reliability.

- Build a Centralized Telemetry Processing System (CTPS) for both ranges, and upgrade the Range Operations Control Centers (ROCC) at the Eastern and Western Ranges.

- Upgrade imaging, surveillance, and weather systems.

- Upgrade debris tracking systems and the multiple objects tracking radar (MOTR) [44:25].

In addition to reducing operations costs and increasing range reliability, availability, and maintainability, the RSA program is designed to provide the following benefits to the Air Force:

- Reduce range reconfiguration times from days to hours
- Standardize range architecture, operations, and logistics support
- Eliminate the need for in-house depot maintenance and fabrication
- Eliminate over 25,000 obsolete range components [44:26]

The Air Force is depending on the RSA program to reduce the complexity and costs of current launch operations. The combination of new expendable launch vehicles and leaner launch infrastructures should allow the United States to maintain its space superiority in the next century. The success of these future systems depends on efficient designs and new, leaner operations.

5 Conclusions and Recommendations

5.1 Overview

This thesis describes how lean thinking can be applied to expendable launch vehicle operations. Given the existing launch infrastructure, launch providers have started to turn inefficient processes into leaner enterprises. Many of these practices can be applied to other expendable launch operations and provide a strong system-level baseline for the next generation of launch vehicles such as the Evolved Expendable Launch Vehicle (EELV). Using the Lean Enterprise Model (LEM) as a guide, launch practices are reviewed to determine lean activities in launch processing cycles. This thesis focuses on the following:

- The Lean Aerospace Initiative (LAI) and the concepts of lean thinking
- A review of current and future launch system requirements and their opportunities for lean practices.
- Analysis of current expendable launch procedures and identification of truly lean, value-added steps in their operations.
- A case study investigating current expendable launch processing operations.
- Results that show how lean principles have helped current launch teams build leaner launch operation enterprises.

5.2 Conclusions

The Lean Enterprise Model adapts well to launch operations. As with any other lean endeavor, the following LEM enterprise principles are applicable to launch operations:

a) Be responsive to change

b) Minimize waste

c) Do the right thing at the right place, time, and quantity

d) Build effective relationships within the value stream

e) Strive for continuous improvement

There are ample opportunities for lean research with respect to medium-lift expendable launch operations. An Aerospace Corporation study states that current U.S. medium expendable launch vehicles (Atlas and Delta class) can deliver an approximate maximum of 29 flights per year [2:60]. The study also forecasts a demand of 30 to 64 medium expendable launches per year in the 2000 to 2010 time frame. Including medium-class EELV and Sea Launch estimates during the same time frame, the forecasted flight rate for U.S. systems is approximately 58 launches per year. To meet such unprecedented demand, launch providers need to build operations enterprises that are better and faster than current practices. In addition to meeting anticipated launch demands, future vehicles are expected to be more responsive to space mission needs and reduce current launch costs by 25 to 50%.

Where to apply lean principles to launch operations is the question. The first of twelve overarching practices listed in the LAI Lean Enterprise Model (LEM) is *identify and optimize flow*. This entails "optimizing the flow of products and services, either affecting or within the process, from concept design through point of use." [32] Launch operation providers can use this practice to analyze launch activity, assess impact on other activities, and determine which activities are necessary, of limited value, or non-value added.

A significant portion of this thesis investigates the launch processing operations of Boeing's medium-lift expendable launch vehicle, the Delta II, at Cape Canaveral Air Station (CCAS), Florida. The Delta team knew the importance of identifying and optimizing enterprise flow, and established a thorough understanding of their launch operations in the process. Identifying the launch flow required them to step back and look at their launch procedures as a complete system of interrelated activities and key in on the activities that slowed the flow. This sounds like a rather simple step, but is often overlooked by many organizations in the process of sub-optimizing activities. Once the enterprise flow is identified, only then can it be optimized. When the Delta team identified their flow, they were able to optimize launch-processing activities by:

- Simulating pad qualification and pre-launch activities
- Determining which launch activities impacted others, and were able to restructure sequence accordingly to avoid "backflow"
- Run most booster pre-launch tests off-pad by driving component testing to earliest opportunity in flow

- Program high-risk procedures off-pad and off the process' critical path
- Better configure flow to meet launch demand

Once an organization has a strong understanding of it enterprise flow, it can then start concentrating on the other lean practices. For instance, after the Delta team identified all their launch activities, it was able to start working on *process capability and maturation.* Maturation practices in the launch flow involved restructuring launch process activities and optimizing test and evaluation procedures. The Delta case study results in Chapter 3 also point out additional LEM practices that can be applied to launch processing activities including:

- Assure seamless information flow
- Continuously focus on the customer
- Promote lean leadership at all levels
- Develop relationships based on mutual trust and commitment
- Maintain challenge of existing processes

By applying lean principles to the launch processing activities, the Delta II launch team has drastically reduced on-pad time, from 40 to 23 work days, restructured its testing philosophy, and streamlined its operations flow. As a result, Boeing is able to offer more competitive launch services to their government and commercial customers. Many of the lessons learned from Delta II process optimization provide a strong foundation for operations of the next generation of launch vehicles such as the EELV.

5.3 Recommendations

Resulting from the Delta II case study are recommended practices that may be incorporated into the Lean Enterprise Model. While the suggested practices are mostly based on the launch operation research gathered in this thesis, they have broad applications to other space operation enterprises. The following list includes specific recommendations and highlights suggested areas of interest for further research.

5.3.1 List of Recommendations

The Lean Enterprise Model's twelve overarching practices and related enabling practices are broadly applicable to launch operations. Furthermore, many of the practices used to improve launch operation flows can be applied to the LEM as supporting practices. This author recommends implementing these supporting practices to the LEM database as listed in the tables at the end of Chapter 3 (Reference Tables 4 - 7).

This author also recommends continued lean-based research in launch operations. Further research opportunities exist in the Delta II launch enterprise. As the Delta II team moved operations off the initial process' critical path and away from the launch pad, it built a shorter critical path to include new off-pad activities. It would be worthwhile to analyze these activities and determine which ones constitute the new critical path, apply to other launch operation enterprises, and are indeed as lean as possible.

While this thesis covers only one aspect of expendable launch operations, it provides a foundation for continued study. Additional areas for research in space launch operations include:

- Current small-lift expendable launch operations involving Orbital Science Corporation's Pegasus and Taurus-class of launch vehicles.
- Other current medium-lift operations to include vehicles in the Lockheed Atlas II family. It would be interesting to compare Atlas II launch operations to the Delta II processes studied in this thesis. It may also be worthwhile to investigate both Atlas and Delta's overseas competition, the European Space Agency's Ariane 4 launch vehicle. The Ariane 4 is known for its innovative launch-processing methods and is considered a strong competitor to U.S. launch providers [27].
- Current heavy-lift expendable launch operations including Titan IV operations.
- Current reusable launch operations involving the Space Shuttle. It would be useful to see what lean practices the United Space Alliance has implemented with the Space Shuttle and determine if they are relevant to proposed future reusable launch vehicle (RLV) operations.
- Future medium and heavy EELV operations. Obviously now is the best time to make sure these important systems come online in the leanest possible ways.

An additional recommendation includes an evaluation of the Range Standardization and Automation (RSA) program. It would be beneficial to both development contractors and Air Force operators to learn where lean principles could be

applied to the crucial launch-infrastructure upgrade program. The RSA program is very broad and it will be necessary to scope research appropriately. Areas of RSA lean operations research may include training, communications, safety, security, hardware development, and operations support procedures.

5.3.2 Policy Recommendations

On a final note, the launch business is at an exciting turning point. Since launch manifests are becoming more populated with commercial launches, the government must realize that it is in the contractor's best interest to provide leaner, reliable, and cost-effective launches. Today's launch system reliability cannot be measured by the adherence to military specifications. As launch companies start providing more sophisticated launch operations that emphasize full efficiency and utilization of lean practices, military process requirements will become less applicable.

Government launch operators should let the contractors forge their own lean paths and learn to be flexible in interfacing with the new, lean principles. The Air Force ought to apply appropriate actions to show launch providers that value-added "insight" will be applied where applicable and wasteful "oversight" removed when unnecessary. It may be appropriate for launch operators and Air Force sponsors to align their thinking to follow that of Brigadier General Robert Hinson, AFSPC/DO, when he states:

> All we want is insight to the process that says: 'You, Mr./Ms. Contractor, have done everything you claimed to do for us to have a successful mission. You have taken into consideration and provided safety, security, and infrastructure protection, so collectively we can have a successful launch.' [Air Force Space Command] will continue to demand a focus on safety, security, and resource protection regardless of the type of system being launched. [19]

A recommended way to provide lean "insight" is to design launch service contracts that focus on the ultimate deliverable item; provide cost-effective, on time, and reliable launches. Officials who draft launch contracts should design them to ensure launch success, but ought to think twice before requiring progress or cost reports that increase launch workload, add little value, and detract from the ultimate launch goal. It will be interesting to see how much insight Air Force Space Command is willing to live with during future launch operations. NASA has transitioned much of its Space Shuttle operations to United Space Alliance. It may be a worthwhile endeavor for an AFIT Space Operations student to compare the NASA example to similar Air Force plans. This research could focus on investigating the historical significance and policy implications of transitioning military launch services to the commercial sector.

5.4 Final Remarks

This thesis attempts to portray the importance of lean implementation in current launch operations. While promising practices are being applied to launch activities, current operations are far from completely lean enterprises. Nevertheless, both launch providers and their customers have a vested interest in continually improving spacelift operations. It is exciting to see the Lean Aerospace Initiative strongly influence the design and operations of the next generation of expendable launch vehicles. Perhaps completely lean launch enterprises are not far in sight.

The concept of lean thinking is more than a set of buzzwords. In the era of limited aerospace funding, lean thinking has become a necessity. Lean space operations can and must be performed for the United States to remain competitive in a global space market and for its Air and Space Force to maintain its superiority in the next millennium.

Appendix A: LAI Member Organizations
(as of Jan 1999)

Principle Investigators and Researchers

Massachusetts Institute of Technology

Air Force Institute of Technology

Avionics/Missiles

Applied Materials Inc.

Hewlett Packard

Lockheed Martin Electronics & Missiles

Raytheon Systems Co.

Textron Systems Division

TRW Inc.

Space

Boeing Space Transportation

Gencorp Aerojet Systems

Hughes Space & Communications

Lockheed Martin Space and Strategic Missiles

Pratt & Whitney Space Propulsion

TRW Inc.

Propulsion

Allison Engine Company

General Electric Aircraft Engines

Pratt & Whitney Gov't Engines

Sundstrand Corp.

Airframe

Lockheed Martin Aeronautical Systems Sector

Northrop Grumman Corp.

Raytheon Aircraft Co.

The Boeing Company (St. Louis, Seattle)

Government

AFRL (Materials and Manufacturing Directorate)

Army Aviation and Missile Command (AMCOM)

Defense Advanced Research Projects Agency (DARPA)

Defense Logistics Agency (DLA)

Deputy of Under Secretary of Defense for Acquisition and Technology (DUSD/A&T)

National Aeronautics and Space Administration (NASA)

Naval Air Systems Command (NAVAIR)

National Reconnaissance Office (NRO)

Space and Missile Systems Center (SMC)

SPOs: JSF, F-22, C-17, Training (JPATS)

Appendix B: The Lean Enterprise Model

Lean Aerospace Initiative

The Lean Enterprise M

The Lean Enterprise Model (LEM) is a systematic framework for organizing and disseminating research results of the Lean Ae encompasses lean enterprise principles and practices and is populated by research-based benchmarking data derived from s and other research activities. The LEM is designed to help LAI members identify and assess the leanness of their own organiz and is intended to help leverage opportunities for organizational change and to support future lean efforts.

1 IDENTIFY AND OPTIMIZE ENTERPRISE FLOW

"Optimize the flow of products and services, either affecting or within the process, from concept design through point of use."

METRICS

- ● Flow Efficiency = actual work time / total flow time
- ✱ ● Throughput
- ▲ ● Order to point of use delivery cycle time
- ● Total PD cycle time, concept to launch

ENABLING PRACTICES

- Establish models and/or simulations to permit understanding and evaluation of the flow process (1,2,4,5,9,11)
- Reduce the number of flow paths (1,4,5,9)
- Minimize inventory through all tiers of the value chain (1,2,4,9,11,12)
- Reduce setup times (1,9)
- Implement process owner inspection throughout the value chain (1,2,3,4,6,9,11)
- Strive for single piece flow (1,2,9,12)
- Minimize space utilized and distance traveled by personnel and material (1,2,3,5,6,7,12)
- Synchronize production and delivery throughout the value chain (1,2,6,9,12)
- Maintain equipment to minimize unplanned stoppages (1,2,3,4,11)

2 ASSURE SEAMLESS INFORMATION FLOW

"Provide processes for seamless and timely transfer of and access to pertinent information."

METRICS

- ✱ Commonality of databases
- ● Information retrieval time
- ✱ Information sharing between customers & suppliers

ENABLING PRACTICES

- Make processes and flows visible to all stakeholders (1,2,4,5,9,11)
- Establish open and timely communications, among all stakeholders (1,2,4,5,6,7,8,9,12)
- Link databases for key functions throughout the value chain (1,2,4,5,9,12)
- Minimize documentation while ensuring necessary data traceability and availability (1,2,4,5,9,11)

3 OPTIMIZE CAPABILITY AND UTILIZATION OF PEOPLE

"Assure properly trained people are available when needed."

METRICS

- ✱ Training hours / employee
- ✱ Output / employee

ENABLING PRACTICES

- Establish career and skill development programs for each employee (3,6,10)
- Ensure maintenance, certification and upgrading of critical skills (2,3,4,10,11)
- Analyze workforce capabilities and needs to provide for balance of breadth and depth of skills/knowledge (1,3,5,8,10,11)
- Broaden jobs to facilitate the development of a flexible workforce (1,3,4,5,10,12)

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▲ **STAKEHOLDER SATISFACTI**
✱ **RESOURCE UTILIZATION** O
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OPTIMIZE APABILITY AND UTILIZATION OF PEOPLE

.ssure properly trained əple are available when needed."

METRICS

Training hours / employee
Output / employee

:ABLING PRACTICES

Establish career and skill development programs for each employee (3,6,10)

Ensure maintenance, certification and upgrading of critical skills (2,3,4,10,11)

Analyze workforce capabilities and needs to provide for balance of breadth and depth of skills/knowledge (1,3,5,8,10,11)

Broaden jobs to facilitate the development of a flexible workforce (1,3,4,5,10,12)

4 MAKE DECISIONS AT LOWEST POSSIBLE LEVEL

"Design the organizational structure and management systems to accelerate and enhance decision making at the point of knowledge, application, and need."

METRICS

✱ # of organizational levels

ENABLING PRACTICES

- Establish multi-disciplinary teams organized around processes and products (1,4,5,9,12)
- Delegate or share responsibility for decisions throughout the value chain (2,4,5,6,8,12)
- Empower people to make decisions at the point of work (2,3,4,5,6,8)
- Minimize hand-offs and approvals within and between line and support activities (1,2,3,4,5,6,9)
- Provide environment and well-defined processes for expedited decision-making (2,4,5,11)

5 IMPLEMENT INTEGRATED PRODUCT AND PROCESS DEVELOPMENT

"Create products through an integrated team effort of people and organizations which are knowledgeable of and responsible for all phases of the product's life cycle from concept definition through development, production, deployment, operations and support, and final disposal."

METRICS

■ # of engineering changes (change traffic) after initial design release
▲ IPT continuity through development cycle
● Total product development cycle time from concept to launch
▲ Supplier involvement in IPTs

ENABLING PRACTICES

- Use systems engineering approach in product design and development (2,5,11,12)
- Establish clear sets of requirements and allocate these to affected elements of the product and processes (1,2,5,6,7,12)
- Definitize risk management (2,5,12)
- Incorporate design for manufacturing, test, maintenance and disposal in all engineering phases (1,2,4,5,7,9,11)
- Design in capability for potential growth & adaptability (5,7,12)
- Establish effective IPTs (4,5,6)
- Involve all stakeholders early in the requirements definition, design and development process (2,4,5,6,7,12)
- Use the "Software Factory" Process (1,5,11)
- Implement design to cost processes (2,5,7,9)
- Maintain continuity of planning throughout the product development process (5,6,7,12)

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PRINCIPLES

Meta-Principles

Responsiveness to Change • Waste Minimization

Enterprise Principles

Right Thing at Right Place, Right Time, and in the Right Quantity

Effective Relationships within the Value Stream

Continuous Improvement

Optimal First Delivered Unit Quality

ENTERPRISE LEVEL METRICS

.OW TIME Order to Delivery Time in Months • Product Development Cycle Time (Industry Comparative, % Reduction)

TAKEHOLDER SATISFACTION On Time Deliveries • Continuous Cost / Price Improvement

:SOURCE UTILIZATION Output / Employee • Inventory Turns

JALITY YIELD Scrap and Rework Rate — Design Changes / Initial Release / Project Phase

OVERARCHING PRACTICES

GRATED
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ble for all phases
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PTs

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elopment
cess (5,6,7,12)

6 DEVELOP RELATIONSHIPS BASED ON MUTUAL TRUST AND COMMITMENT

"Establish stable and on-going cooperative relationships within the extended enterprise, encompassing both customers and suppliers."

METRICS

- ▲ # of strategic alliances / total # of direct suppliers
- ▲ # of projects w/customers on IPTs
- * ▲ % of procurement dollars purchased under long-term supplier agreements
- ▲ # of years of relationship with suppliers
- ▲ Existence of formal communications programs

ENABLING PRACTICES

- Build stable and cooperative relationships internally and externally (2,5,4,6,7,12)
- Establish labor-management partnerships (3,6,8)
- Strive for continued employment or employability of the workforce (3,6,9,10)
- Provide for mutual sharing of benefits from implementation of lean practices (5,6,9)
- Establish common objectives among all stakeholders (6,7,9,10,12)

7 CONTINUOUSLY FOCUS ON THE CUSTOMER

"Proactively understand and respond to the needs of the internal and external customers."

METRICS

- ● ▲ Customer access to supplier information
- ▲ % of projects w/ customers on IPTs
- ▲ On time delivery from source to point of use

ENABLING PRACTICES

- Provide for continuous information flow and feedback with stakeholders (2,4,5,7,9,11,12)
- Optimize the contract process to be flexible to learning and changing requirements (6,7,9,10,11,12)
- Create and maintain relationships with customers in requirements generation, product design, development and solution-based problem solving (5,6,7,9)

8 PROMOTE L LEADERSI AT ALL LEV

"Align and invo
stakeholders to ac
enterprise's lean

METRICS

- ▲ Lean metrics levels

ENABLING PRA

- Flow-down lea principles, prac and metrics to organizational (1,2,3,4,5,6,7,8. 11,12)
- Instill individua ownership throughout the workforce in al products and services that a provided (1,3,4,5,6,7,8,9,
- Assure consist of enterprise st with lean princi and practices (4,6,8,12)
- Involve union leadership in promoting and implementing l practices (1,3,4,5,6,8,9,1

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The LEM is presently available on-line for al!
please visit http://web.mit.edu/lean or cont:

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8 PROMOTE LEAN LEADERSHIP AT ALL LEVELS

"Align and involve all stakeholders to achieve the enterprise's lean vision."

METRICS

▲ Lean metrics at all levels

ENABLING PRACTICES

- Flow-down lean principles, practices and metrics to all organizational levels (1,2,3,4,5,6,7,8,9,10, 11,12)
- Instill individual ownership throughout the workforce in all products and services that are provided (1,3,4,5,6,7,8,9,10,11)
- Assure consistency of enterprise strategy with lean principles and practices (4,6,8,12)
- Involve union leadership in promoting and implementing lean practices (1,3,4,5,6,8,9,10,11)

9 MAINTAIN CHALLENGE OF EXISTING PROCESSES

"Ensure a culture and systems that use quantitative measurement and analysis to continuously improve processes."

METRICS

✱ # of repeat problems

▲ Customer assistance to suppliers

ENABLING PRACTICES

- Establish structured processes for generating, evaluating and implementing improvements at all levels (1,2,3,4,5,9,11)
- Fix problems systematically using data and root cause analysis (3,9,11)
- Utilize cost accounting/ management systems to establish the discrete cost of individual parts and activities (1,2,9)
- Set jointly-established targets for continuous improvement at all levels and in all phases of the product life cycle (1,4,6,7,8,9,11)
- Incentivize initiatives for beneficial, innovative practices (1,6,9,11)

10 NURTURE A LEARNING ENVIRONMEN

"Provide for the develo|
and growth of bot|
organizations' and indivi
support of attaining l
enterprise goals."

METRICS

✱ ▲ Training hours / employee

● Use of "lessons learned" system

▲ Provision of suppl training programs

ENABLING PRACTIC

- Capture, communicate and apply experience-generated learning (2,3,4,9,10)
- Perform benchmarking (9,10,11)
- Provide for interchange of knowledge from an within the supplier network (1,6,9,10,1

e LEM: An On-Line Tool

's presently available on-line for all LAI members and their authorized suppliers. For more information about on-line access, it http://web.mit.edu/lean or contact your local LAI Point-of-Contact for more details.*

**A complete member listing with Points-of-Contact is also available on-line at http://web.mit.edu/lean*

10 NURTURE A LEARNING ENVIRONMENT

"Provide for the development and growth of both organizations' and individuals' support of attaining lean enterprise goals."

METRICS

- ✱ ▲ Training hours / employee
- ● Use of "lessons learned" system
- ▲ Provision of supplier training programs

ENABLING PRACTICES

- Capture, communicate and apply experience-generated learning (2,3,4,9,10)
- Perform benchmarking (9,10,11)
- Provide for interchange of knowledge from and within the supplier network (1,6,9,10,11)

11 ENSURE PROCESS CAPABILITY AND MATURATION

"Establish and maintain processes capable of consistently designing and producing the key characteristics of the product or service."

METRICS

- ■ C_{pk}
- ✱ ■ Scrap, rework & repair as % of cost
- ■ Software productivity
- ✱ # of suppliers certified
- ■ Engineering changes (change traffic)
- ■ Lean practices adoption

ENABLING PRACTICES

- Define and control processes throughout the value chain (1,2,3,4,5,9,11)
- Establish cost beneficial variability reduction practices in all phases of product life cycle (9,11)
- Establish make/buy as a strategic decision (11,12)

12 MAXIMIZE STABILITY IN A CHANGING ENVIRONMENT

"Establish strategies to maintain program stability in a changing customer driven environment."

METRICS

- ▲ ■ Schedule changes
- ■ # of baseline changes / year
- ▲ ■ # of program restructures
- ✱ Procurement quantity changes
- ■ Program administration continuity

ENABLING PRACTICES

- Level demand to enable continuous flow (1,6,9,12)
- Use multi-year contracting wherever possible (4,6,12)
- Minimize cycle-time to limit susceptibility to externally imposed changes (1,9,12)
- Structure programs to absorb changes with minimal impact (5,11,12)
- Establish incremental product performance objectives where possible (5,9,12)
- Program high risk developments off critical paths and/or provide alternatives (1,5,12)

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Appendix C: Modern ELV Successes and Failures *through Oct 1998* [1]

Titan 4	*Success*	*22*	*Failure*	*2*	
			Marginal	*1*	
Program	**Result**	**Flight No.**	**Tail/Serial No.**	**Vehicle Type**	**Launch Date**
Titan IVA 402	success	313	K-1	launch vehicle	6/14/89
Titan IVA 405	success	318	K-4	launch vehicle	6/8/90
Titan IVA 402	success	320	K-6	launch vehicle	11/12/90
Titan IVA 403	marginal	321	K-5	launch vehicle	3/8/91
Titan IVA 403	success	322	K-8	launch vehicle	11/8/91
Titan IVA 404	success	325	K-3	launch vehicle	11/28/92
Titan IVA 403	failure	326	K-11	launch vehicle	8/2/93
Titan IVA 401	success	329	K-10	launch vehicle	2/7/94
Titan IVA 401	success	330	K-7	launch vehicle	5/3/94
Titan IVA 401	success	331	K-9	launch vehicle	8/27/94
Titan IVA 402	success	332	K-14	launch vehicle	12/22/94
Titan IVA 401	success	333	K-23	launch vehicle	5/14/95
Titan IVA 401	success	334	K-19	launch vehicle	7/10/95
Titan IVA 401	success	335	K-21	launch vehicle	11/6/95
Titan IVA 404	success	336	K-15	launch vehicle	12/5/95
Titan IVA 401	success	337	K-16	launch vehicle	4/24/96
Titan IVA 403	success	338	K-22	launch vehicle	5/12/96
Titan IVA 403	success	339	K-2	launch vehicle	7/3/96
Titan IVA 404	success	340	K-13	launch vehicle	12/20/96
Titan IVB 402	success	341	K-24	launch vehicle	2/23/97
Titan IVA 403	success	343	A-18	launch vehicle	10/24/97
Titan IVB 401	success	344	B-33	launch vehicle	10/15/97
Titan IVA 401	success	345	A-17	launch vehicle	11/8/97
Titan IVB 401	success	348	B-25	launch vehicle	5/9/98
Titan IVA 401	failure	349	A-20	launch vehicle	8/12/98

Delta II	*Success*	*71*	*Failure*	*2*	
Program	**Result**	**Flight No.**	**Tail/Serial No.**	**Vehicle Type**	**Launch Date**
Delta II 6925	success	183	184	launch vehicle	2/14/89
Delta II 6925	success	185	185	launch vehicle	6/10/89
Delta II 6925	success	186	186	launch vehicle	8/18/89
Delta II 6925	success	188	188	launch vehicle	10/21/89
Delta II 6925	success	190	190	launch vehicle	12/11/89
Delta II 6925	success	191	191	launch vehicle	1/24/90
Delta II 6920-8	success	192	192	launch vehicle	2/14/90
Delta II 6925	success	193	193	launch vehicle	3/26/90
Delta II 6925-8	success	194	194	launch vehicle	4/13/90
Delta II 6920-10	success	195	195	launch vehicle	6/1/90
Delta II 6925	success	197	197	launch vehicle	8/2/90

Delta II 6925-8	success	198	198	launch vehicle	8/18/90
Delta II 6925	success	199	199	launch vehicle	10/1/90
Delta II 6925	success	200	200	launch vehicle	10/30/90
Delta II 7925	success	201	201	launch vehicle	11/26/90
Delta II 7925	success	202	202	launch vehicle	1/8/91
Delta II 6925	success	203	203	launch vehicle	3/8/91
Delta II 7925	success	204	204	launch vehicle	4/13/91
Delta II 7925	success	205	205	launch vehicle	5/29/91
Delta II 7925	success	206	206	launch vehicle	7/4/91
Delta II 7925	success	207	207	launch vehicle	2/23/92
Delta II 7925	success	208	208	launch vehicle	4/10/92
Delta II 7925-8	success	209	209	launch vehicle	5/14/92
Delta II 6920-10	success	210	210	launch vehicle	6/7/92
Delta II 7925	success	211	211	launch vehicle	7/7/92
Delta II 6925	success	212	212	launch vehicle	7/24/92
Delta II 7925	success	213	213	launch vehicle	8/31/92
Delta II 7925	success	214	214	launch vehicle	9/9/92
Delta II 7925	success	215	215	launch vehicle	10/12/92
Delta II 7925	success	216	216	launch vehicle	11/22/92
Delta II 7925	success	217	217	launch vehicle	12/18/92
Delta II 7925	success	218	218	launch vehicle	2/3/93
Delta II 7925	success	219	219	launch vehicle	3/30/93
Delta II 7925	success	220	220	launch vehicle	5/13/93
Delta II 7925	success	221	221	launch vehicle	6/26/93
Delta II 7925	success	222	222	launch vehicle	8/30/93
Delta II 7925	success	223	223	launch vehicle	10/26/93
Delta II 7925	success	224	224	launch vehicle	12/8/93
Delta II 7925-8	success	225	225	launch vehicle	2/19/94
Delta II 7925	success	226	226	launch vehicle	3/10/94
Delta II 7925	success	227	227	launch vehicle	11/1/94
Delta II 7925	failure	228	228	launch vehicle	8/5/95
Delta II 7920	success	229	229	launch vehicle	11/4/95
Delta II 7920-10	success	230	230	launch vehicle	12/30/95
Delta II 7925	success	231	231	launch vehicle	1/14/96
Delta II 7925-8	success	232	232	launch vehicle	2/17/96
Delta II 7925	success	233	233	launch vehicle	2/24/96
Delta II 7925	success	234	234	launch vehicle	3/28/96
Delta II 7925	success	235	235	launch vehicle	4/24/96
Delta II 7925	success	236	236	launch vehicle	5/24/96
Delta II 7925	success	237	237	launch vehicle	7/16/96
Delta II 7925	success	238	238	launch vehicle	9/12/96
Delta II 7925	success	239	239	launch vehicle	11/7/96
Delta II 7925	success	240	240	launch vehicle	12/4/96
Delta II 7925	failure	241	241	launch vehicle	1/17/97
Delta II 7920-10	success	242	242	launch vehicle	5/5/97
Delta IIA 7925	success	243	243	launch vehicle	5/20/97
Delta II 7920-10	success	244	244	launch vehicle	7/9/97

Delta II 7925	success	245	245	launch vehicle	7/23/97
Delta II 7920-10	success	246	246	launch vehicle	8/21/97
Delta II 7920-8	success	247	247	launch vehicle	8/25/97
Delta II 7920-10	success	248	248	launch vehicle	9/27/97
Delta II 7925-9	success	249	249	launch vehicle	11/6/97
Delta II 7920-10	success	250	250	launch vehicle	11/9/97
Delta II 7920-10	success	251	251	launch vehicle	12/20/97
Delta II 7925	success	252	252	launch vehicle	1/10/98
Delta II 7420-10	success	253	253	launch vehicle	2/14/98
Delta II 7920-10C	success	254	254	launch vehicle	2/18/98
Delta II 7920-10	success	255	255	launch vehicle	3/30/98
Delta II 7420	success	256	256	launch vehicle	4/24/98
Delta II 7920-10C	success	257	257	launch vehicle	5/17/98
Delta II 7925	success	258	258	launch vehicle	6/10/98
Delta II 7920	success	260	260	launch vehicle	9/8/98

Atlas II ***Success 39*** ***Failure 0***

Program	Result	Flight No.	Tail/Serial No.	Vehicle Type	Launch Date
Atlas II	success	501	AC-102	launch vehicle	12/7/91
Atlas II	success	502	AC-101	launch vehicle	2/11/92
Atlas IIA	success	504	AC-105	launch vehicle	6/10/92
Atlas II	success	505	AC-103	launch vehicle	7/2/92
Atlas II	success	508	AC-104	launch vehicle	7/19/93
Atlas II	success	511	AC-106	launch vehicle	11/28/93
Atlas IIAS	success	512	AC-108	launch vehicle	12/16/93
Atlas IIA	success	515	AC-107	launch vehicle	8/3/94
Atlas IIAS	success	517	AC-111	launch vehicle	10/6/94
Atlas IIA	success	518	AC-110	launch vehicle	11/29/94
Atlas IIAS	success	520	AC-113	launch vehicle	1/10/95
Atlas II	success	521	AC-112	launch vehicle	1/29/95
Atlas IIAS	success	522	AC-115	launch vehicle	3/22/95
Atlas IIA	success	524	AC-114	launch vehicle	4/7/95
Atlas II	success	526	AC-116	launch vehicle	5/31/95
Atlas IIA	success	527	AC-118	launch vehicle	7/31/95
Atlas IIAS	success	528	AC-117	launch vehicle	8/29/95
Atlas II	success	529	AC-119	launch vehicle	10/22/95
Atlas IIAS	success	530	AC-121	launch vehicle	12/2/95
Atlas IIA	success	531	AC-120	launch vehicle	12/15/95
Atlas IIAS	success	532	AC-126	launch vehicle	2/1/96
Atlas IIA	success	533	AC-122	launch vehicle	4/3/96
Atlas II	success	535	AC-125	launch vehicle	7/25/96
Atlas IIA	success	536	AC-123	launch vehicle	9/8/96
Atlas IIA	success	537	AC-124	launch vehicle	11/21/96
Atlas IIA	success	538	AC-129	launch vehicle	12/18/96
Atlas IIAS	success	539	AC-127	launch vehicle	2/17/97
Atlas IIA	success	540	AC-128	launch vehicle	3/8/97

Atlas IIAS	success	541	AC-133	launch vehicle	7/27/97
Atlas IIAS	success	542	AC-146	launch vehicle	9/4/97
Atlas IIAS	success	543	AC-135	launch vehicle	10/5/97
Atlas IIA	success	544	AC-131	launch vehicle	10/24/97
Atlas IIAS	success	545	AC-149	launch vehicle	12/8/97
Atlas IIA	success	546	AC-109	launch vehicle	1/29/98
Atlas IIAS	success	547	AC-151	launch vehicle	2/28/98
Atlas IIAS	success	548	AC-153	launch vehicle	6/18/98
Atlas II	success	549	AC-132	launch vehicle	3/16/98
Atlas IIA	success	549	AC-134	launch vehicle	10/9/98
Atlas IIA	success	552	AC-130	launch vehicle	10/20/98

Russian Proton D-1 and D-1-e (Since Jan 1970) *Successes: 211 Failures: 26*

Program	Result	Flight No.	Tail/Serial No.	Vehicle Type	Launch Date
Proton K D-1-e (SL-12)	failure	21	x21	launch vehicle	1/30/70
Proton K D-1-e (SL-12)	success	23	x23	launch vehicle	9/12/70
Proton K D-1-e (SL-12)	success	24	x24	launch vehicle	10/20/70
Proton K D-1-e (SL-12)	success	25	x25	launch vehicle	11/10/70
Proton K D-1 (SL-13)	success	26	x26	launch vehicle	11/24/70
Proton K D-1-e (SL-12)	success	27	x27	launch vehicle	12/2/70
Proton K D-1 (SL-13)	success	28	x28	launch vehicle	2/26/71
Proton K D-1 (SL-13)	success	29	x29	launch vehicle	4/19/71
Proton K D-1-e (SL-12)	failure	30	x30	launch vehicle	5/10/71
Proton K D-1-e (SL-12)	success	31	x31	launch vehicle	5/19/71
Proton K D-1-e (SL-12)	success	32	x32	launch vehicle	5/28/71
Proton K D-1-e (SL-12)	success	33	x33	launch vehicle	9/2/71
Proton K D-1-e (SL-12)	success	34	x34	launch vehicle	9/28/71
Proton K D-1-e (SL-12)	success	35	x35	launch vehicle	2/14/72
Proton K D-1 (SL-13)	failure	36	x36	launch vehicle	7/29/72
Proton K D-1-e (SL-12)	success	37	x37	launch vehicle	1/8/73
Proton K D-1 (SL-13)	failure	38	x38	launch vehicle	4/3/73
Proton K D-1 (SL-13)	failure	39	x39	launch vehicle	5/11/73
Proton K D-1-e (SL-12)	failure	40	x40	launch vehicle	7/21/73
Proton K D-1-e (SL-12)	success	41	x41	launch vehicle	7/25/73
Proton K D-1-e (SL-12)	success	42	x42	launch vehicle	8/5/73
Proton K D-1-e (SL-12)	success	43	x43	launch vehicle	8/9/73
Proton K D-1-e (SL-12)	success	44	x44	launch vehicle	3/26/74
Proton K D-1-e (SL-12)	success	45	x45	launch vehicle	5/29/74
Proton K D-1 (SL-13)	success	46	x46	launch vehicle	6/24/74
Proton K D-1-e (SL-12)	success	47	x47	launch vehicle	7/29/74
Proton K D-1-e (SL-12)	success	48	x48	launch vehicle	10/28/74
Proton K D-1 (SL-13)	success	49	x49	launch vehicle	12/26/74
Proton K D-1-e (SL-12)	success	50	x50	launch vehicle	6/8/75
Proton K D-1-e (SL-12)	success	51	x51	launch vehicle	6/14/75
Proton K D-1-e (SL-12)	success	52	x52	launch vehicle	10/8/75
Proton K D-1-e (SL-12)	failure	53	x53	launch vehicle	10/16/75
Proton K D-1-e (SL-12)	success	54	x54	launch vehicle	12/22/75
Proton K D-1 (SL-13)	success	55	x55	launch vehicle	6/22/76
Proton K D-1-e (SL-12)	success	56	x56	launch vehicle	8/9/76
Proton K D-1-e (SL-12)	success	57	x57	launch vehicle	9/11/76
Proton K D-1-e (SL-12)	success	58	x58	launch vehicle	10/26/76
Proton K D-1 (SL-13)	success	59	x59	launch vehicle	12/15/76

Proton K D-1 (SL-13)	success	60	x60	launch vehicle	7/17/77
Proton K D-1-e (SL-12)	success	61	x61	launch vehicle	7/23/77
Proton K D-1 (SL-13)	**failure**	62	x62	launch vehicle	8/4/77
Proton K D-1-e (SL-12)	success	63	x63	launch vehicle	9/20/77
Proton K D-1 (SL-13)	success	64	x64	launch vehicle	9/29/77
Proton K D-1-e (SL-12)	**failure**	65	x65	launch vehicle	10/14/77
Proton K D-1 (SL-13)	success	66	x66	launch vehicle	3/30/78
Proton K D-1-e (SL-12)	**failure**	67	x67	launch vehicle	5/27/78
Proton K D-1-e (SL-12)	success	68	x68	launch vehicle	7/18/78
Proton K D-1-e (SL-12)	**failure**	69	x69	launch vehicle	8/17/78
Proton K D-1-e (SL-12)	success	70	x70	launch vehicle	9/9/78
Proton K D-1-e (SL-12)	success	71	x71	launch vehicle	9/14/78
Proton K D-1-e (SL-12)	**failure**	72	x72	launch vehicle	10/17/78
Proton K D-1-e (SL-12)	**failure**	73	x73	launch vehicle	12/19/78
Proton K D-1-e (SL-12)	success	74	x74	launch vehicle	2/21/79
Proton K D-1-e (SL-12)	success	75	x75	launch vehicle	4/25/79
Proton K D-1 (SL-13)	success	76	x76	launch vehicle	5/22/79
Proton K D-1-e (SL-12)	success	77	x77	launch vehicle	7/5/79
Proton K D-1-e (SL-12)	success	78	x78	launch vehicle	10/3/79
Proton K D-1-e (SL-12)	success	79	x79	launch vehicle	12/28/79
Proton K D-1-e (SL-12)	success	80	x80	launch vehicle	2/20/80
Proton K D-1-e (SL-12)	success	81	x81	launch vehicle	6/15/80
Proton K D-1-e (SL-12)	success	82	x82	launch vehicle	7/14/80
Proton K D-1-e (SL-12)	success	83	x83	launch vehicle	10/5/80
Proton K D-1-e (SL-12)	success	84	x84	launch vehicle	12/26/80
Proton K D-1-e (SL-12)	success	85	x85	launch vehicle	3/18/81
Proton K D-1 (SL-13)	success	86	x86	launch vehicle	4/25/81
Proton K D-1-e (SL-12)	success	87	x87	launch vehicle	6/26/81
Proton K D-1-e (SL-12)	success	88	x88	launch vehicle	7/30/81
Proton K D-1-e (SL-12)	success	89	x89	launch vehicle	10/9/81
Proton K D-1-e (SL-12)	success	90	x90	launch vehicle	10/30/81
Proton K D-1-e (SL-12)	success	91	x91	launch vehicle	11/4/81
Proton K D-1-e (SL-12)	success	92	x92	launch vehicle	2/5/82
Proton K D-1-e (SL-12)	success	93	x93	launch vehicle	3/15/82
Proton K D-1 (SL-13)	success	94	x94	launch vehicle	4/19/82
Proton K D-1-e (SL-12)	success	95	x95	launch vehicle	5/17/82
Proton K D-1-e (SL-12)	**failure**	96	x96	launch vehicle	7/23/82
Proton K D-1-e (SL-12)	success	97	x97	launch vehicle	9/16/82
Proton K D-1-e (SL-12)	success	98	x98	launch vehicle	10/12/82
Proton K D-1-e (SL-12)	success	99	x99	launch vehicle	10/20/82
Proton K D-1-e (SL-12)	success	100	x100	launch vehicle	11/26/82
Proton K D-1-e (SL-12)	**failure**	101	x101	launch vehicle	12/24/82
Proton K D-1 (SL-13)	success	102	x102	launch vehicle	3/2/83
Proton K D-1-e (SL-12)	success	103	x103	launch vehicle	3/12/83
Proton K D-1-e (SL-12)	success	104	x104	launch vehicle	3/23/83
Proton K D-1-e (SL-12)	success	105	x105	launch vehicle	4/8/83
Proton K D-1-e (SL-12)	success	106	x106	launch vehicle	6/2/83
Proton K D-1-e (SL-12)	success	107	x107	launch vehicle	6/7/83
Proton K D-1-e (SL-12)	success	108	x108	launch vehicle	6/30/83
Proton K D-1-e (SL-12)	success	109	x109	launch vehicle	8/10/83
Proton K D-1-e (SL-12)	success	110	x110	launch vehicle	8/25/83
Proton K D-1-e (SL-12)	success	111	x111	launch vehicle	9/29/83
Proton K D-1-e (SL-12)	success	112	x112	launch vehicle	11/30/83
Proton K D-1-e (SL-12)	success	113	x113	launch vehicle	12/29/83
Proton K D-1-e (SL-12)	success	114	x114	launch vehicle	2/15/84
Proton K D-1-e (SL-12)	success	115	x115	launch vehicle	3/2/84
Proton K D-1-e (SL-12)	success	116	x116	launch vehicle	3/16/84
Proton K D-1-e (SL-12)	success	117	x117	launch vehicle	3/29/84

Proton K D-1-e (SL-12)	success	118	x118	launch vehicle	4/22/84
Proton K D-1-e (SL-12)	success	119	x119	launch vehicle	5/19/84
Proton K D-1-e (SL-12)	success	120	x120	launch vehicle	6/22/84
Proton K D-1-e (SL-12)	success	121	x121	launch vehicle	8/1/84
Proton K D-1-e (SL-12)	success	122	x122	launch vehicle	8/24/84
Proton K D-1-e (SL-12)	success	123	x123	launch vehicle	9/4/84
Proton K D-1-e (SL-12)	success	124	x124	launch vehicle	9/28/84
Proton K D-1-e (SL-12)	success	125	x125	launch vehicle	12/15/84
Proton K D-1-e (SL-12)	success	126	x126	launch vehicle	12/21/84
Proton K D-1-e (SL-12)	success	127	x127	launch vehicle	1/18/85
Proton K D-1-e (SL-12)	success	128	x128	launch vehicle	2/21/85
Proton K D-1-e (SL-12)	success	129	x129	launch vehicle	3/22/85
Proton K D-1-e (SL-12)	success	130	x130	launch vehicle	5/17/85
Proton K D-1-e (SL-12)	success	131	x131	launch vehicle	5/30/85
Proton K D-1-e (SL-12)	success	132	x132	launch vehicle	8/8/85
Proton K D-1 (SL-13)	success	133	x133	launch vehicle	9/27/85
Proton K D-1-e (SL-12)	success	134	x134	launch vehicle	10/25/85
Proton K D-1-e (SL-12)	success	135	x135	launch vehicle	11/15/85
Proton K D-1-e (SL-12)	success	136	x136	launch vehicle	12/24/85
Proton K D-1-e (SL-12)	success	137	x137	launch vehicle	1/17/86
Proton K D-1 (SL-13)	success	138	x138	launch vehicle	2/19/86
Proton K D-1-e (SL-12)	success	139	x139	launch vehicle	4/4/86
Proton K D-1-e (SL-12)	success	140	x140	launch vehicle	5/24/86
Proton K D-1-e (SL-12)	success	141	x141	launch vehicle	6/10/86
Proton K D-1-e (SL-12)	success	142	x142	launch vehicle	9/16/86
Proton K D-1-e (SL-12)	success	143	x143	launch vehicle	10/25/86
Proton K D-1-e (SL-12)	success	144	x144	launch vehicle	11/18/86
Proton K D-1 (SL-13)	**failure**	145F	x145F	launch vehicle	12/29/86
Proton K D-1-e (SL-12)	**failure**	145	x145	launch vehicle	1/30/87
Proton K D-1-e (SL-12)	success	146	x146	launch vehicle	3/19/87
Proton K D-1 (SL-13)	success	147	x147	launch vehicle	3/31/87
Proton K D-1-e (SL-12)	**failure**	148	x148	launch vehicle	4/24/87
Proton K D-1-e (SL-12)	success	149	x149	launch vehicle	5/11/87
Proton K D-1 (SL-13)	success	150	x150	launch vehicle	7/25/87
Proton K D-1-e (SL-12)	success	151	x151	launch vehicle	9/3/87
Proton K D-1-e (SL-12)	success	153	x153	launch vehicle	9/16/87
Proton K D-1-e (SL-12)	success	154	x154	launch vehicle	10/1/87
Proton K D-1-e (SL-12)	success	155	x155	launch vehicle	10/28/87
Proton K D-1-e (SL-12)	success	156	x156	launch vehicle	11/26/87
Proton K D-1-e (SL-12)	success	157	x157	launch vehicle	12/10/87
Proton K D-1-e (SL-12)	success	158	x158	launch vehicle	12/27/87
Proton K D-1-e (SL-12)	**failure**	159F	x159F	launch vehicle	1/18/88
Proton K D-1-e (SL-12)	**failure**	159	x159	launch vehicle	2/17/88
Proton K D-1-e (SL-12)	success	160	x160	launch vehicle	3/31/88
Proton K D-1-e (SL-12)	success	161	x161	launch vehicle	4/26/88
Proton K D-1-e (SL-12)	success	162	x162	launch vehicle	5/6/88
Proton K D-1-e (SL-12)	success	163	x163	launch vehicle	5/21/88
Proton K D-1-e (SL-12)	success	164	x164	launch vehicle	7/7/88
Proton K D-1-e (SL-12)	success	165	x165	launch vehicle	7/12/88
Proton K D-1-e (SL-12)	success	166	x166	launch vehicle	8/1/88
Proton K D-1-e (SL-12)	success	167	x167	launch vehicle	8/18/88
Proton K D-1-e (SL-12)	success	168	x168	launch vehicle	9/16/88
Proton K D-1-e (SL-12)	success	169	x169	launch vehicle	10/20/88
Proton K D-1-e (SL-12)	success	170	x170	launch vehicle	12/10/88
Proton K D-1-e (SL-12)	success	171	x171	launch vehicle	1/10/89
Proton K D-1-e (SL-12)	success	172	x172	launch vehicle	1/26/89
Proton K D-1-e (SL-12)	success	173	x173	launch vehicle	4/14/89
Proton K D-1-e (SL-12)	success	174	x174	launch vehicle	5/31/89

Proton K D-1-e (SL-12)	success	175	x175	launch vehicle	6/21/89
Proton K D-1-e (SL-12)	success	176	x176	launch vehicle	7/5/89
Proton K D-1-e (SL-12)	success	177	x177	launch vehicle	9/28/89
Proton K D-1 (SL-13)	success	178	x178	launch vehicle	11/26/89
Proton K D-1-e (SL-12)	success	179	x179	launch vehicle	12/1/89
Proton K D-1-e (SL-12)	success	180	x180	launch vehicle	12/15/89
Proton K D-1-e (SL-12)	success	181	x181	launch vehicle	12/27/89
Proton K D-1-e (SL-12)	success	182	x182	launch vehicle	2/15/90
Proton K D-1-e (SL-12)	success	183	x183	launch vehicle	5/19/90
Proton K D-1 (SL-13)	success	184	x184	launch vehicle	5/31/90
Proton K D-1-e (SL-12)	success	185	x185	launch vehicle	6/20/90
Proton K D-1-e (SL-12)	success	186	x186	launch vehicle	7/18/90
Proton K D-1-e (SL-12)	**failure**	187	x187	launch vehicle	8/9/90
Proton K D-1-e (SL-12)	**failure**	188F	x188F	launch vehicle	8/29/90
Proton K D-1-e (SL-12)	success	188	x188	launch vehicle	11/3/90
Proton K D-1-e (SL-12)	success	189	x189	launch vehicle	11/23/90
Proton K D-1-e (SL-12)	success	190	x190	launch vehicle	12/8/90
Proton K D-1-e (SL-12)	success	191	x191	launch vehicle	12/20/90
Proton K D-1-e (SL-12)	success	192	x192	launch vehicle	12/27/90
Proton K D-1-e (SL-12)	success	193	x193	launch vehicle	2/14/91
Proton K D-1-e (SL-12)	success	194	x194	launch vehicle	2/28/91
Proton K D-1 (SL-13)	success	195	x195	launch vehicle	3/31/91
Proton K D-1-e (SL-12)	success	196	x196	launch vehicle	4/4/91
Proton K D-1-e (SL-12)	success	197	x197	launch vehicle	7/1/91
Proton K D-1-e (SL-12)	success	198	x198	launch vehicle	9/13/91
Proton K D-1-e (SL-12)	success	199	x199	launch vehicle	10/23/91
Proton K D-1-e (SL-12)	success	200	x200	launch vehicle	11/22/91
Proton K D-1-e (SL-12)	success	201	x201	launch vehicle	12/19/91
Proton K D-1-e (SL-12)	success	202	x202	launch vehicle	1/29/92
Proton K D-1-e (SL-12)	success	203	x203	launch vehicle	4/2/92
Proton K D-1-e (SL-12)	success	204	x204	launch vehicle	7/14/92
Proton K D-1-e (SL-12)	success	205	x205	launch vehicle	7/30/92
Proton K D-1-e (SL-12)	success	206	x206	launch vehicle	9/10/92
Proton K D-1-e (SL-12)	success	207	x207	launch vehicle	10/30/92
Proton K D-1-e (SL-12)	success	208	x208	launch vehicle	11/27/92
Proton K D-1-e (SL-12)	success	209	x209	launch vehicle	12/17/92
Proton K D-1-e (SL-12)	success	210	x210	launch vehicle	2/17/93
Proton K D-1-e (SL-12)	success	211	x211	launch vehicle	3/25/93
Proton K D-1-e (SL-12)	**failure**	212	x212	launch vehicle	5/27/93
Proton K D-1-e (SL-12)	success	213	x213	launch vehicle	9/30/93
Proton K D-1-e (SL-12)	success	214	x214	launch vehicle	10/28/93
Proton K D-1-e (SL-12)	success	215	x215	launch vehicle	11/18/93
Proton K D-1-e (SL-12)	success	216	x216	launch vehicle	1/20/94
Proton K D-1-e (SL-12)	success	217	x217	launch vehicle	2/5/94
Proton K D-1-e (SL-12)	success	218	x218	launch vehicle	2/18/94
Proton K D-1-e (SL-12)	success	219	x219	launch vehicle	4/11/94
Proton K D-1-e (SL-12)	success	220	x220	launch vehicle	5/20/94
Proton K D-1-e (SL-12)	success	221	x221	launch vehicle	7/6/94
Proton K D-1-e (SL-12)	success	222	x222	launch vehicle	8/11/94
Proton K D-1-e (SL-12)	success	223	x223	launch vehicle	9/21/94
Proton K D-1-e (SL-12)	success	224	x224	launch vehicle	10/13/94
Proton K D-1-e (SL-12)	success	225	x225	launch vehicle	10/31/94
Proton K D-1-e (SL-12)	success	226	x226	launch vehicle	11/20/94
Proton K D-1-e (SL-12)	success	227	x227	launch vehicle	12/16/94
Proton K D-1-e (SL-12)	success	228	x228	launch vehicle	12/28/94
Proton K D-1-e (SL-12)	success	229	x229	launch vehicle	3/7/95
Proton K D-1 (SL-13)	success	230	x230	launch vehicle	5/20/95
Proton K D-1-e (SL-12)	success	231	x231	launch vehicle	7/24/95

Proton K D-1-e (SL-12)	success	232	x232	launch vehicle	8/30/95
Proton K D-1-e (SL-12)	success	233	x233	Launch vehicle	10/11/95
Proton K D-1-e (SL-12)	success	234	x234	launch vehicle	11/17/95
Proton K D-1-e (SL-12)	success	235	x235	launch vehicle	12/14/95
Proton K D-1-e (SL-12)	success	236	x236	launch vehicle	1/25/96
Proton K D-1-e (SL-12)	**failure**	237	x237	launch vehicle	2/19/96
Proton K D-1-e (SL-12)	success	238	x238	launch vehicle	4/8/96
Proton K D-1 (SL-13)	success	239	x239	launch vehicle	4/23/96
Proton K D-1-e (SL-12)	success	240	x240	launch vehicle	5/25/96
Proton K D-1-e (SL-12)	success	241	x241	launch vehicle	9/6/96
Proton K D-1-e (SL-12)	success	242	x242	launch vehicle	9/26/96
Proton K D-1-e (SL-12)	**failure**	243	x243	launch vehicle	11/16/96
Proton K D-1-e (SL-12)	success	244	x244	launch vehicle	5/24/97
Proton K D-1-e (SL-12)	success	245	x245	launch vehicle	6/6/97
Proton K D-1-e (SL-12)	success	246	x246	launch vehicle	6/18/97
Proton K D-1-e (SL-12)	success	247	x247	launch vehicle	8/14/97
Proton K D-1-e (SL-12)	success	248	x248	launch vehicle	8/28/97
Proton K D-1-e (SL-12)	success	249	x249	launch vehicle	9/14/97
Proton K D-1-e (SL-12)	success	250	x250	launch vehicle	11/11/97
Proton K D-1-e (SL-12)	success	251	x251	launch vehicle	12/2/97
Proton K D-1-e (SL-12)	**failure**	252	x252	launch vehicle	12/24/97
Proton K D-1 (SL-13)	success	253	x253	launch vehicle	4/7/98
Proton K D-1-e (SL-12)	success	254	x254	launch vehicle	4/29/98
Proton K D-1 (SL-13)	success	255	x255	launch vehicle	5/7/98
Proton K D-1-e (SL-12)	success	F261	x256	launch vehicle	8/30/98

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Vita

Captain Troy Lynd Endicott was born 15 April 1971 in Morristown, NJ. After spending his youth living in the states of Maine, New Hampshire, Tennessee, and Washington he graduated from West Valley High School in Yakima, WA in 1989. Captain Endicott then attended Embry-Riddle Aeronautical University in Prescott, Arizona, and received a Bachelor of Science Degree in Aerospace Engineering. Having been commissioned a Second Lieutenant in the United States Air Force in May 1994, his first assignment was to the Aeronautical Systems Center at Wright-Patterson AFB, Ohio. After a short term as a test project officer at the Tri-Service Standoff Attack Missile System Program Office (SPO), he was assigned to the Reconnaissance System Program Office. At the Reconnaissance SPO, he was a project and test manager for airborne reconnaissance projects such as an advanced airborne electro-optical sensor program, a U-2 aircraft multi-spectral imagery (MSI) flight-test program, and a PACOM imagery dissemination program. In 1996, he directly supported the deployment and operations of the Rapid Targeting System (RTS) "sensor-to-shooter" advanced technology demonstrator for Bosnian air operations. In July 1997, he attended Undergraduate Space and Missile Training (USMT) at Vandenberg, AFB and was selected to attend the Air Force Institute of Technology School of Engineering to receive a Masters of Science Degree in Space Operations. His follow-on assignment after AFIT is to the 533 Training Squadron at Schriever AFB, Colorado. Captain Endicott is married to the former Tammy J.D. Farr of California's San Francisco Bay Area.

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This study analyzes current expendable launch procedures and identifies truly lean, value-added steps in launch operation enterprises as they relate to the Lean Aerospace Initiative (LAI). LAI and the concepts of lean thinking are discussed and followed by a review of current and future launch system requirements and their opportunities for lean practices. The study also discusses in detail current Delta II expendable launch processing operations and presents results in a case study that show how lean principles have helped the Delta II launch team drastically reduce on-pad time, restructure its testing philosophy, and streamline its operations flow. Many of these practices can be applied to re-engineering other expendable launch operations and provide a strong systems baseline for the next generation of launch vehicles such as the Evolved Expendable Launch Vehicle (EELV).

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